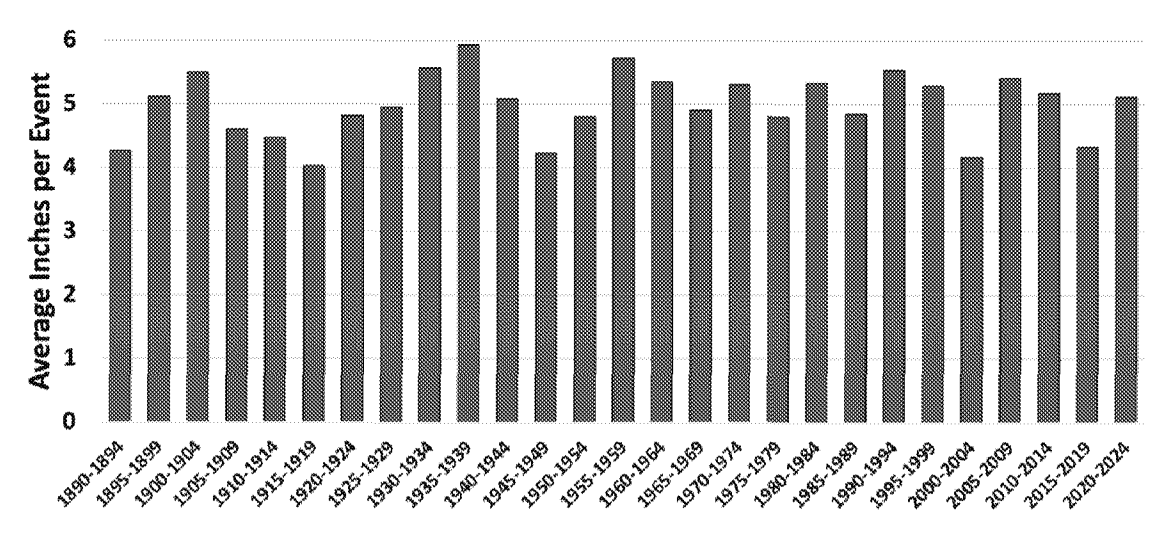


England Hurricane of 1938, one of the rare major (Category 3 or higher) hurricanes to strike the region. The results in Figs. 6.5.5 and 6.5.6 thus suggest that though there was a surge in the number of events at a few locations during the 1995 to 2014 interval, there was no regional pattern and the change did not persist beyond 2014.



**Figure 6.5.6.** Average amount of precipitation falling in the 1-in-5yr events for the NE stations.

Jong et al. (2024) document the increase of tropical influences on precipitation events in the Northeast since 1959 and concluded, “The autumn extreme precipitation trend over the Northeast US is primarily attributed to tropical cyclone-related events since the 1990s.” The question then becomes: was the temporal clustering of tropical systems in 1997-2014 which affected the Northeast a response to increasing GHGs? Jong et al. examined CMIP-6 model output which suggests that there will be fewer such systems in the 21<sup>st</sup> century but that the intensity of the rainfall events might increase. This conjecture is not seen in Fig. 6.5.6 where the amount-per-event has remained steady over the 135-year period.

There is some evidence to indicate the heaviest rainfall events may be redistributed due to the impact urban infrastructure has on the local weather (e.g., Pielke Sr. et al. 2011, Zhang et al. 2018, Yang et al. 2024). Yang et al. state, “Cities that experience compact development tend to witness larger increases in extreme rainfall frequency over downtown than their rural surroundings, while the anomalies in extreme rainfall frequency diminish for cities with dispersed development.” While this is an important insight to consider, the effect on the specific stations used in this analysis is unknown, or at least not detectable in Fig. 6.5.5.

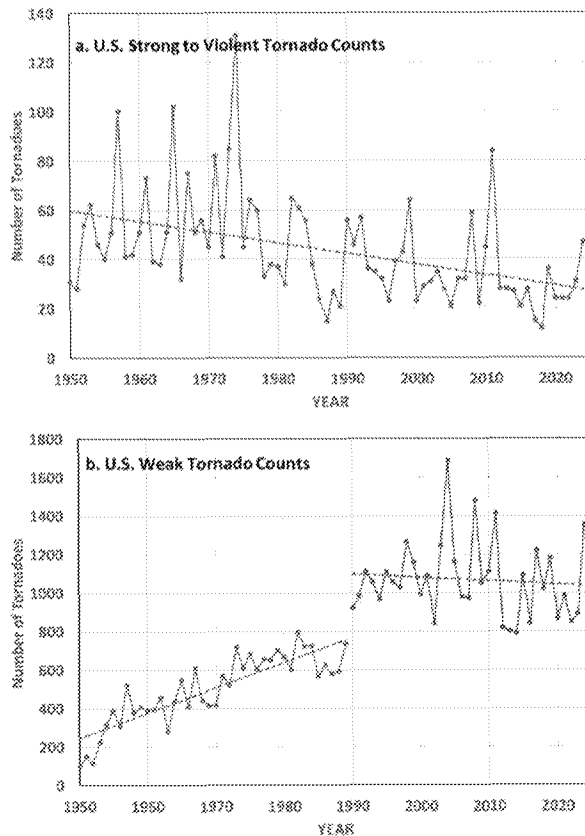
In summary, some regions show short-interval increases in extreme precipitation events, consistent with natural variability. But analysis of long term, nationwide historical records taking into account the autocorrelation properties of precipitation data does not support the claim that extreme short-duration rainfall events are becoming more frequent or intense.

## 6.5 Tornadoes

AR6 assesses tornado trends in the US as follows:

[O]bservational trends in tornadoes, hail, and lightning associated with severe convective storms are not robustly detected due to insufficient coverage of the long-term observations. There is *medium confidence* that the mean annual number of tornadoes in the USA has remained relatively constant. (Chapter 11, section 11.7.3, p. 1594)

The monitoring of weak tornadoes has changed over time. The growth of rural populations and the increasing ability to take video with hand-held devices has led to more frequent reports of weak tornadoes that produce minimal damage. In contrast, strong to violent tornadoes have been observed more consistently over time. Since statistics began in 1950, there has been a substantial decrease (by about 50%) in the number of strong to violent tornadoes as shown in Fig. 6.6.1a. Note that tornado strength is measured by the damage it produces, not by the visual appearance of the funnel. Limited real-time observational capabilities in earlier decades did not prevent identification because strong to violent tornadoes leave much more damage which will be assessed later even if the tornado itself was not observed.



**Figure 6.6.1.** Annual U.S. tornado counts for (a) strong to violent tornadoes (EF3 to EF5), and (b) weak tornadoes (EF0 to EF2). Based upon NOAA Storms Prediction Center data, available at [https://www.spc.noaa.gov/wcm/data/1950-2024\\_actual\\_tornadoes.csv](https://www.spc.noaa.gov/wcm/data/1950-2024_actual_tornadoes.csv)



To summarize, there is a noticeable downward trend in the number of severe tornadoes in the U.S. since 1950. After 1990 the number of weak tornadoes in the U.S. has remained roughly constant; data before that are incomplete due to limited monitoring.

## 6.6 Flooding

Changes in floods were assessed as follows:

AR6: “The SREX **assessed low confidence for observed changes in the magnitude or frequency of floods** at the global scale. This assessment was confirmed by the AR5 report. The SR15 found increases in flood frequency and extreme streamflow in some regions, but decreases in other regions. . . [H]ydrological literature on observed flood changes is heterogeneous, focusing at regional and sub-regional basin scales, making it difficult to synthesise at the global and sometimes regional scales.” (Chapter 11.5)

AR6: “[T]he seasonality of floods has changed in cold regions where snowmelt dominates the flow regime in response to warming (*high confidence*). Confidence about peak flow trends over past decades on the global scale is **low**.” (Chapter 11.5)

NCA4: “Trends in extreme high values of streamflow are **mixed** across the United States. Analysis of 200 U.S. stream gauges indicates areas of both increasing and decreasing flooding magnitude **but does not provide robust evidence** that these trends are attributable to human influences” (pp. 240-241)

The absence of detectable US-wide trends in flooding is consistent with the findings in Section 6.5 of absence of coherent changes in extreme precipitation.

## 6.7 Droughts

Assessments of drought trends were as follows.

AR6: “**Few** AR6 regions show observed increases in meteorological drought” (Section 11.9, p. 1575),

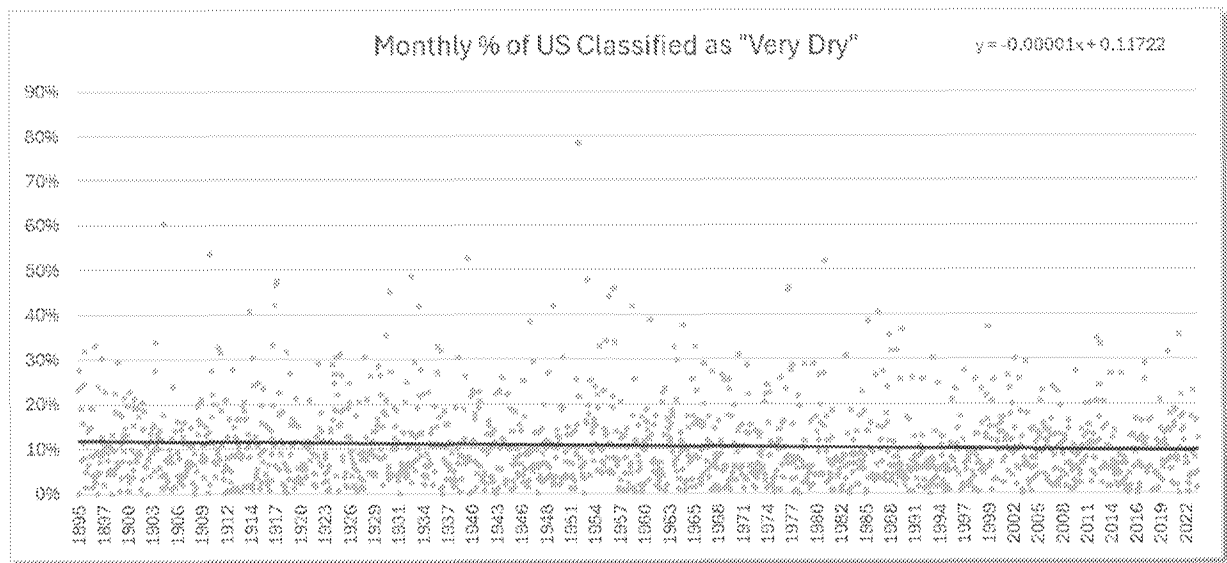
AR6: “**Increasing trends in agricultural and ecological droughts have been observed on all continents** (*medium confidence*), but decreases only in one AR6 region (*medium confidence*). Increasing trends in hydrological droughts have been observed in a few AR6 regions.” (Chapter 11 Summary)

NCA4: “As a consequence of this increased precipitation, **drought statistics over the entire CONUS have declined**.” (p. 233)

NCA4: “Recent droughts and associated heat waves have reached record intensity in some regions of the United States; however, by geographical scale and duration, the Dust Bowl era of the **1930s remains the benchmark** drought and extreme heat event in the historical record (very high confidence).” (p.231)

SREX: “From a paleoclimate perspective, **recent droughts are not unprecedented**, with severe ‘megadroughts’ reported in the paleoclimatic record for Europe, North America, and Australia.” (p. 170)

As shown in Figure 6.8.1, US long term data shows an insignificantly declining trend toward extreme dryness (-0.0001% per year)



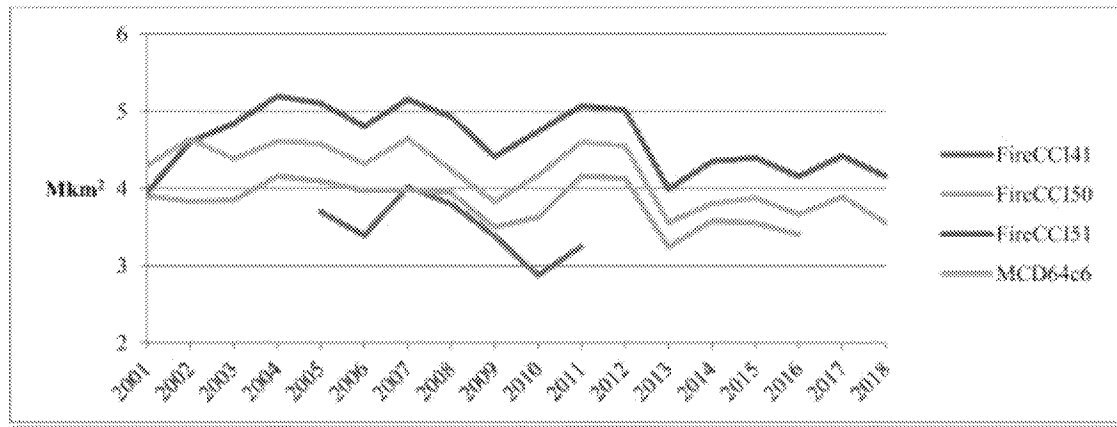
**Figure 6.8.1:** US dryness (%) 1895—2023. Source: NOAA [ [HYPERLINK "https://www.ncei.noaa.gov/access/monitoring/uspa/wet-dry/0" \]](https://www.ncei.noaa.gov/access/monitoring/uspa/wet-dry/0) ]

Kogan et al. (2020) examines a 38-year high-resolution satellite-based drought measure and concludes that global drought has not intensified and is not connected to climate change: “it is possible to state firmly that global and main grain countries’ drought area and intensity trends have not been following global climate warming since 1980’s.”

In summary there is no evidence of increasing drought frequency or intensity in the U.S. or globally over recent decades.

## 6.8 Wildfires

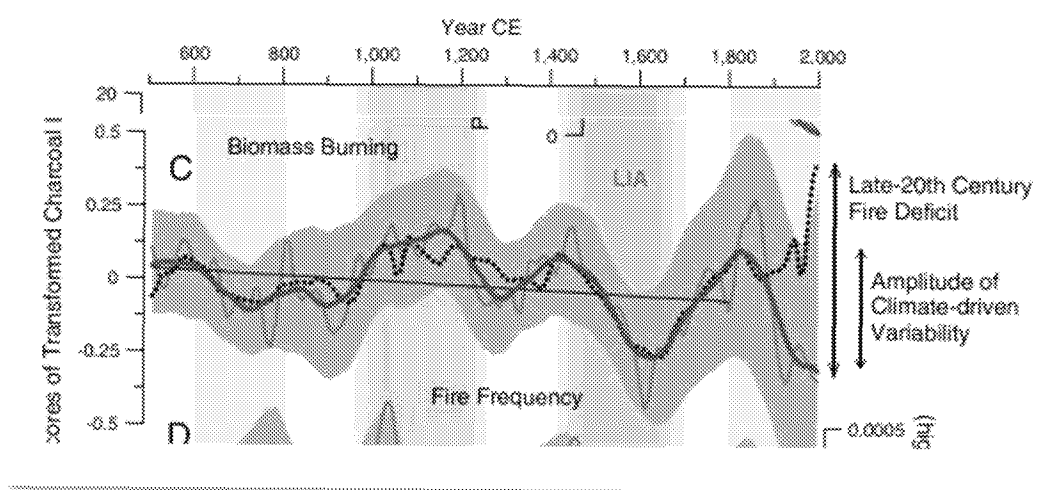
The IPCC has not provided an assessment of wildfires. As shown in Figure 6.9.1, global wildfire activity as measured by European Space Agency shows a downward trend in the 21<sup>st</sup> century.



**Figure 6.9.1:** Global wildfire area 2001-2018. Source: From Lizundia-Loiola et al. (2021). The different coloured lines represent data products derived from different satellites and algorithms

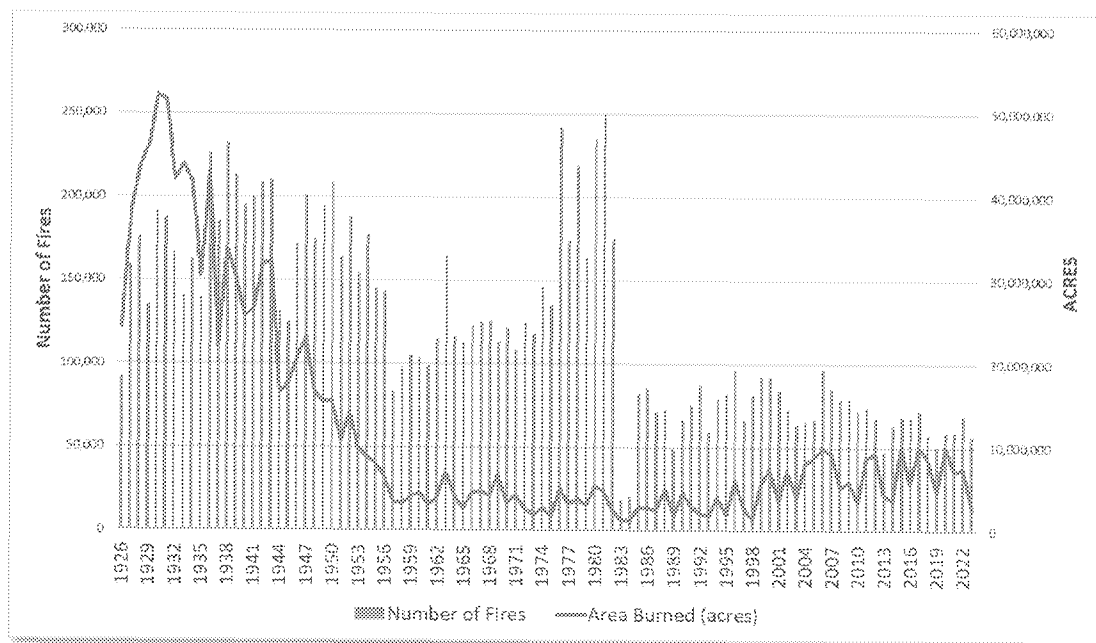
Global data show that wildfire coverage is constant or declining on every continent (Samborska and Ritchie 2024).

Active fire suppression since 1900 makes it difficult to establish a natural baseline for wildfire activity in the U.S. Paleoclimatic evidence indicates that past activity was much higher than today. Marlon et al. (2012) used sedimentary charcoal layers to reconstruct fire history of western US for the past 1400 years and also fit a model to predict fire activity as a function of climatic conditions. Their results are summarized in Figure 6.9.3 below (from Figure 2 in their paper). There has been a growing wildfire deficit over the 20<sup>th</sup> century. In other words, however much fire was observed in the 20<sup>th</sup> century, it was less than what would have been observed in previous centuries based on the climatic conditions. Parks et al. (2025) likewise find that despite the recent increase in wildfire burn area in North America, a significant wildfire deficit remains relative to historical wildfire regimes.



**Figure 6.9.2** Fire frequency and fire deficit in the US. The red line shows the smoothed charcoal record and the black dotted line shows the predicted charcoal record based on climatic conditions. Source: Copied from Marlon et al. (2012)

US data from the National Interagency Fire Centre (NIFC) from 1926 to 2023 are shown in Figure 6.9.2.



**Figure 6.9.2:** US wildfires 1926 to 2023. Source: Post-2018: National InterAgency Fire Center data Pre-2017 webarchive.org.

The NIFC has removed the pre-1960 data from its current website on the grounds that measurement methods changed after 1960 making the comparison unreliable. Nonetheless just focusing on the post-1985 interval the number of fires is not increasing. The area burned did increase but only until about 2007.

Forest fires have always been a part of nature, and they can certainly create conditions that are inhospitable in the short term for all life including humans. Science has confirmed the overall benefit and necessity of the occurrence of forest fires. While recent high-profile fires and seasons serve as a reminder of the potential destructive impact, the highest profile forest fire remains the 1910 Big Blowup fire which destroyed over three million acres including the elimination of entire towns like Taft, MT (Apple 2020). The 1910 fire reshaped the U.S. Forest Service (National Forest Foundation 2022) leading to a focus on fire suppression with a primary goal to defeat all forest fires (Forest History Society 2022). This led to the 10 am rule in 1935 requiring that all fires spotted on any day had to be controlled by 10 am the following day (National Forest Foundation 2022).

While defeating all fires seemed a noble goal, questions began to arise as to whether this behavior “followed the science” (US Forest Service 2022). Over time the U.S. Forest Service has begun to rethink its goals, recognizing that new approaches such as prescribed burns, fuel elimination, and controlled wildfires are more appropriate (Sommer 2016). Recent research is validating this approach and recognizing that more frequent smaller fires likely result in the healthier forests, water ecosystems and biodiversity (Stephens et al. 2021).

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## 7 CHANGES IN SEA LEVEL

### Chapter Summary

*Since 1900, global average sea level has risen by about 8 inches. Sea level change along U.S. coasts is highly variable, associated with local variations in processes that contribute to sinking and also ocean circulation patterns. The highest levels of sea level rise along U.S. coasts are Galveston, New Orleans, and the Chesapeake Bay regions - each of these locations is associated with substantial local land sinking (subsidence) unrelated to climate change.*

*Extreme projections of global sea level rise are associated with an implausible extreme emissions scenario and inclusion of poorly understood processes associated with hypothesized ice sheet instabilities. In evaluating the IPCC AR6 projections to 2050 (with reference to the baseline period 1995-2014), almost half of the sea level rise has already occurred by 2025 and at a lower rate than predicted. US tide gauge measurements shown herein reveal no obvious acceleration beyond the historical average rate of sea level rise.*

### 7.1 Global sea level rise

Global sea level rise is arguably the most important climate impact driver that is unambiguously associated with increasing temperatures. At the global level, warming raises sea level through thermal expansion of the volume of sea water and through melting of glaciers and ice sheets. Variations in land water storage are another important factor. At the regional scale, sea level change is influenced by large-scale ocean circulation patterns, and geologic processes and deformation from the redistribution of ice and water. Locally, vertical land motion from geologic processes, ground water withdrawal, and fossil fuel extraction are also important.

The IPCC AR6 estimates that global mean sea level increased by 7.9 (5.9–9.8) inches between 1901 and 2018, with the rate of sea level rise accelerating in recent decades. At the ocean basin scale, sea levels have risen fastest in the Western Pacific and slowest in the Eastern Pacific over the period 1993–2018 (B. Fox-Kemper et al., 2021). The rate of global sea level rise is estimated to be 0.12 inches/year (for reference, 0.12 in is the height of two stacked pennies) (NASA, 2020).

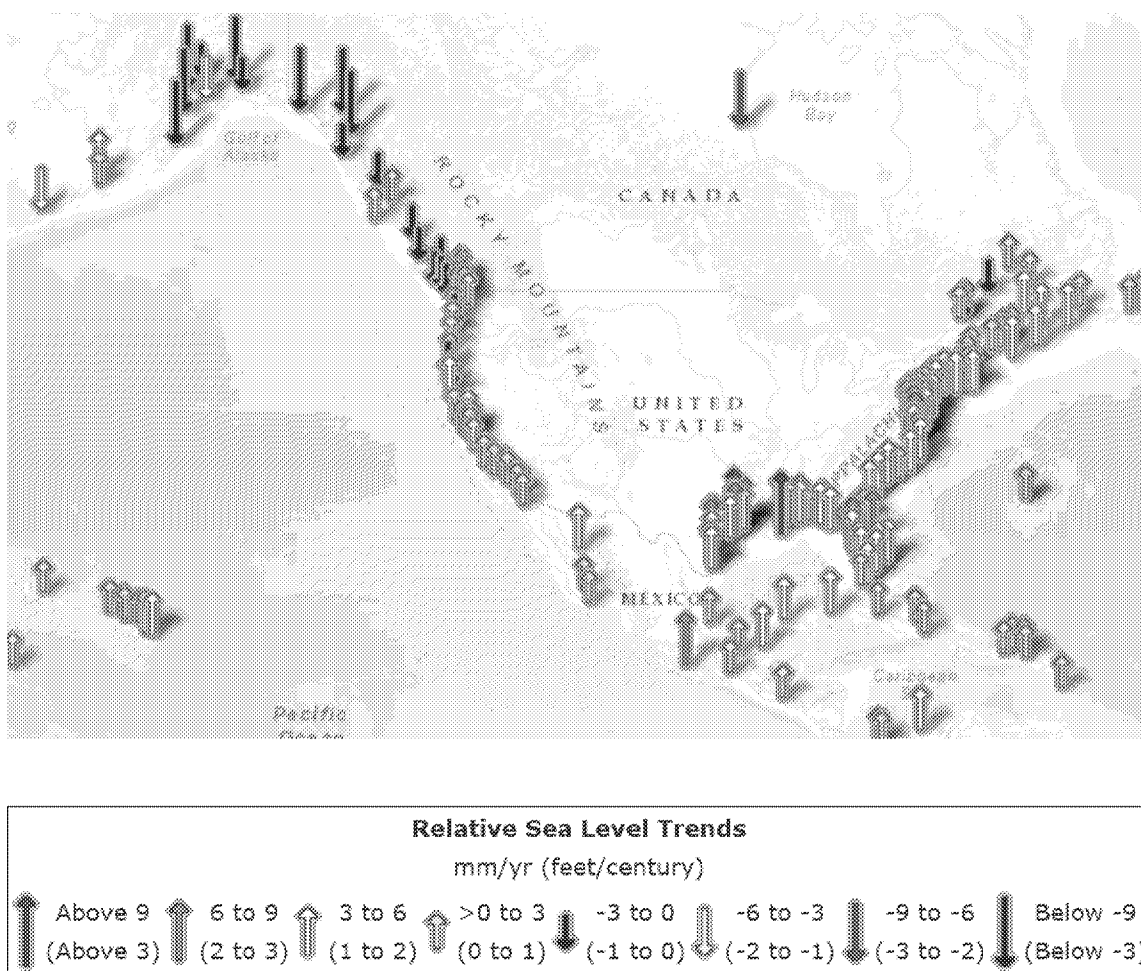
The observing systems for global sea level rise have advanced significantly in the satellite era, particularly with the advent of satellite altimeters since 1993. Local tide gauges have provided useful data for the past century, and even longer for a few locations. Following the end of the Little Ice Age in the mid-nineteenth century, tide gauges show that the global mean sea level began rising during the period 1820–1860, well before most anthropogenic greenhouse gas emissions.

### 7.2 U.S. sea level rise

Observed and predicted rates of mean global sea level rise might have little scientific relevance for specific locations, owing to local processes (NOAA, 2025). Figure 7.1 shows that in Canada and Alaska (and also northern Washington), sea level is actually decreasing, owing to uplift from glacial rebound. Most

of the Pacific coast tide gauges show rises between 0.12 inches/year, while largest U.S. rates are on the Gulf coast (Louisiana and Texas) and in the mid-Atlantic states (Chesapeake Bay region).

Measurements of relative sea level rise from tide gauges conflate the climatologically relevant increase in the volume of seawater with local vertical land motion. That latter, which varies from place to place, is best measured using a Global Positioning System (GPS) station located near the tide gauge. It is driven by a range of processes that can be comparable to the climate signal and can locally exacerbate (subsidence/sinking) or mitigate (uplift) the risk of sea level rise (G Wöppelmann and M Marcos, 2016). Human activities triggering subsidence are often significant. They include soil drainage (e.g. for urban development purposes) and subsurface extraction of groundwater, oil, or gas.



**Figure 7.1.** Map of rates of relative sea level rise along the U.S. coast (NOAA, <https://tidesandcurrents.noaa.gov/sltrends/>). For reference, 3 mm = 0.12 in.

Table 7.1 shows absolute sea-level rise (ASLR) for selected locations, determined from the sum of uncorrected sea-level rise as estimated from tide gauge time series (RSLR) (NOAA, 2025) and the vertical land motion (VLM) measurements (NAS, 2012; Letetrel et al., 2015; Karegar et al., 2016). The absolute

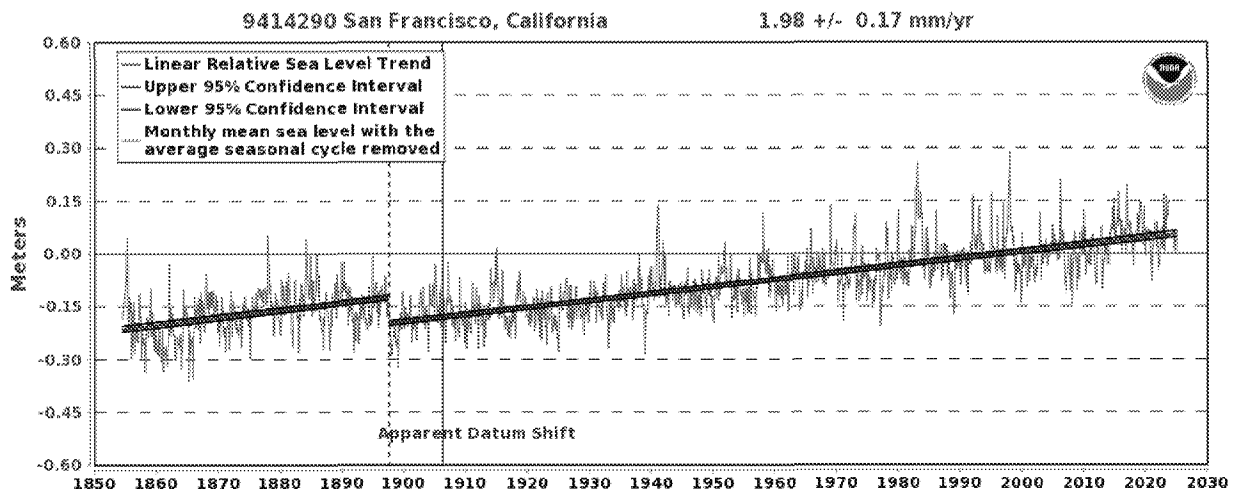
sea level rise for each of these locations is significantly smaller than the measured relative sea level rise owing to local subsidence. More than half of the measured relative sea level rise is attributed to land sinking for these locations: San Francisco, Galveston, Grand Isle. For reference, the global average rate of absolute sea level rise is estimated to be 0.12 inches/year.

| Location          | RSLR  | VLM   | ASLR  |
|-------------------|-------|-------|-------|
| San Francisco, CA | +0.08 | -0.06 | +0.02 |
| Galveston, TX     | +0.26 | -0.19 | +0.07 |
| Grand Isle, LA    | +0.36 | -0.28 | +0.08 |
| St Petersburg, FL | +0.12 | -0.02 | +0.10 |
| New York City, NY | +0.11 | -0.05 | +0.06 |

**Table 7.1** Absolute sea level rise (inches/year) (Relative Sea Level Rise (RSLR) plus Vertical Land Motion (VLM))

### *San Francisco Bay*

Over the past 100 years, relative sea level in the San Francisco Bay area has risen by 7.8 inches, at an average rate of 0.08 inches/year (Figure 7.2). As shown in Table 7.1, San Francisco's vertical land motion is -0.06 inches/year (sinking), producing a recent absolute rate of +0.02 inches/year. Portions of Treasure Island, San Francisco International Airport, and Foster City are sinking as fast as 0.4 inches/year (M Shirzaei and R Bürgmann, 2018). Problems in the San Francisco Bay area, including threats to the airport, have been caused primarily by soil compaction in landfill zones that were formerly wetlands, not by the slow creep of global sea level rise.

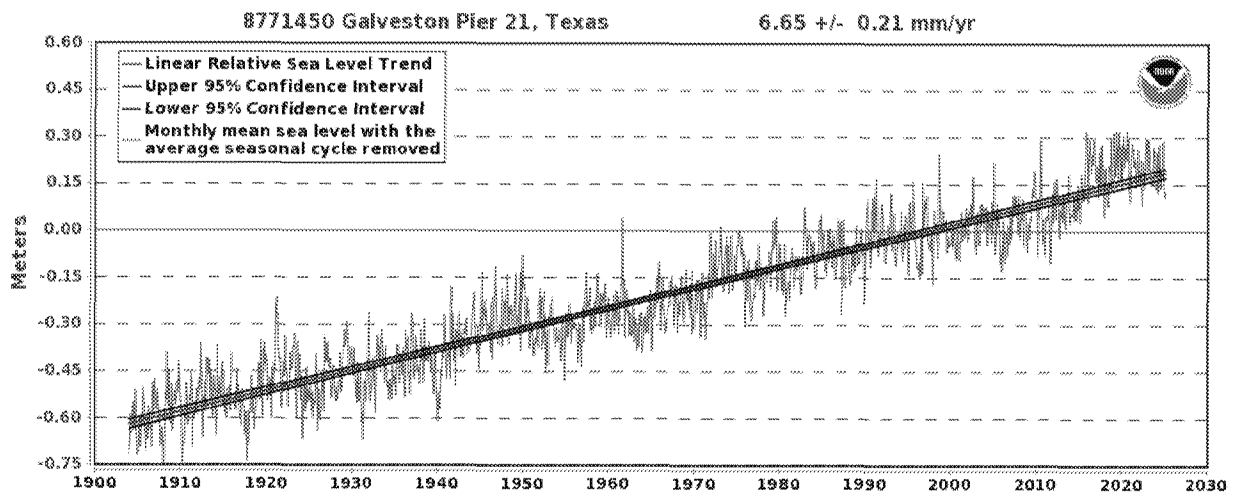


**Figure 7.2.** Tide gauge measurements at San Francisco, California, obtained from NOAA - [https://tidesandcurrents.noaa.gov/sltrends/sltrends\\_station.shtml?id=9414290](https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=9414290) (downloaded 4/22/25).

### *Galveston - Houston*

Long-term tide measurements at Galveston Pier 21 show sea level rise of 2.18 feet in the past century, or a rate of 0.26 inches/year (Figure 7.3). Vertical land motion (subsidence) at Galveston is estimated at -0.19 inches/year, yielding an absolute rate of rise of +0.07 inches/year (Table 7.1). The U.S. Geologic Survey found that most of the land-surface subsidence in the Houston-Galveston region is a direct result of groundwater withdrawals (Kasmarek and Ramage), which caused compaction of the aquifer sediments, mostly in the fine-grained silt and clay layers. By 1979, as much as 10 feet of subsidence had occurred in Houston.

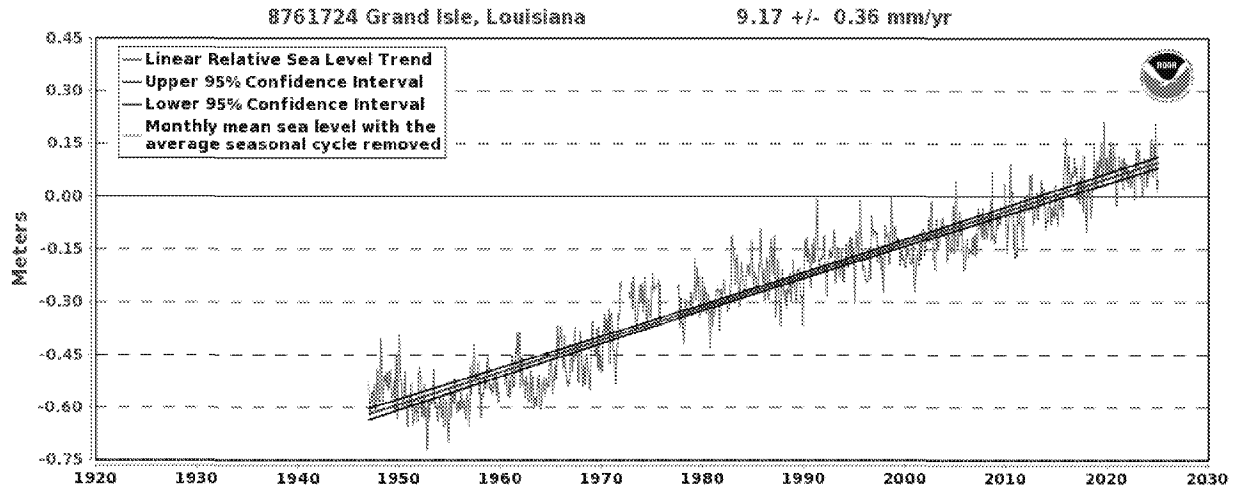
Hurricanes have been the major concern in the region. The 1900 hurricane that struck Galveston and killed between 6,000 and 12,000 people is still considered the deadliest U.S. natural disaster (Weems, 2016). Hurricane Ike (2008) decimated large portions of the Bolivar Peninsula, literally removing significant portions of the land mass (UCS, 2017). While only 17 people were killed in Texas, property damage exceeded \$50 billion (White, 2017). In 2017, Hurricane Harvey struck the region, bringing catastrophic rainfall-triggered flooding that inflicted over \$125 billion in damages (NOAA, 2025).



**Figure 7.3.** Tide gauge measurements Galveston Pier, TX, obtained from NOAA - [https://tidesandcurrents.noaa.gov/sltrends/sltrends\\_station.shtml?id=8771450](https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8771450) (downloaded 4/22/2025).

### *New Orleans and the Mississippi delta*

Long-term tide gauge measurements at Grand Isle, Louisiana, show that sea level has risen by slightly more than 3 feet over the last 100 years at an average rate of 0.36 inches/year (Figure 7.4). Vertical land motion (subsidence) is estimated -0.28 inches/year. Table 7.1 gives the absolute sea level rise as +0.08 inches/year.

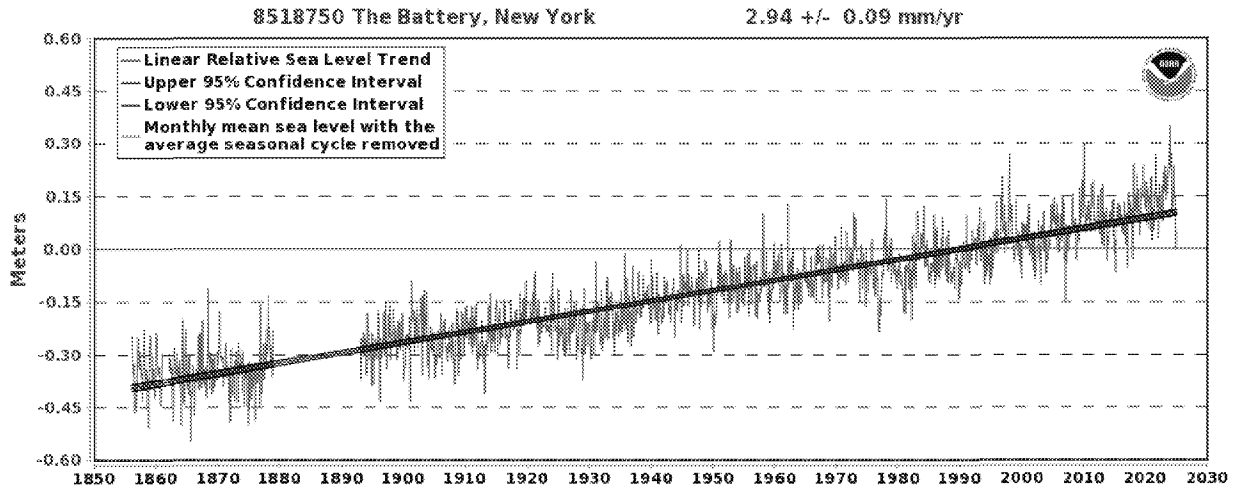


**Figure 7.4.** Tide gauge measurements at Grand Isle, LA, obtained from NOAA - [https://tidesandcurrents.noaa.gov/sltrends/sltrends\\_station.shtml?id=8761724](https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8761724) (downloaded 4/22/25).

The issues of sea level rise and land loss in the Mississippi Delta region are complex, with geological subsidence and the decline in sediment transported by the Mississippi river being the dominant drivers. The construction of dams in the basin since the 1950s has decreased the Mississippi's suspended sediment load by ~50% (Malooney, 2018). A new subsidence map of coastal Louisiana finds the coastal region to be sinking at about one third of an inch per year (Neinhuis et al., 2017), associated with groundwater and resource withdrawal. As the city's elevation averages one to two feet *below* sea level, sea level rise from anthropogenic warming is hardly the dominant driver of New Orleans' problems.

#### *New York City*

New York City is particularly vulnerable to the effects of sea level rise because it is built primarily on islands and has 520 miles of coastline. Measurements by a tide gauge at the southern tip of Manhattan (The Battery) show that relative sea level has risen over 11 inches over the past century, at an average rate of 0.11 inches/year (Figure 7.5). But vertical land motion in the New York City area is -0.05 inches/year (roughly 5 inches per century), so that the absolute rate of sea level rise at The Battery is 0.06 inches/year, or about 55% of the measured relative sea level rise.



**Figure 7.5.** Tide gauge measurements at The Battery, New York, obtained from NOAA - [https://tidesandcurrents.noaa.gov/sltrends/sltrends\\_station.shtml?id=8518750](https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8518750) (downloaded 4/22/25).

Following Superstorm Sandy, New York developed a comprehensive plan: [ [HYPERLINK "http://s-media.nyc.gov/agencies/sirr/SIRR\\_singles\\_Hi\\_res.pdf"](http://s-media.nyc.gov/agencies/sirr/SIRR_singles_Hi_res.pdf) ] (CNY,2013). A broad range of coastal protection measures are outlined that match the risks facing the various zones: increase coastal edge elevations, minimize upland wave zones, infrastructure to protect against storm surge, improve coastal design and governance, restore estuaries wetlands, coastal nourishment, site elevation, and drainage systems.

### 7.3 Projected sea level rise

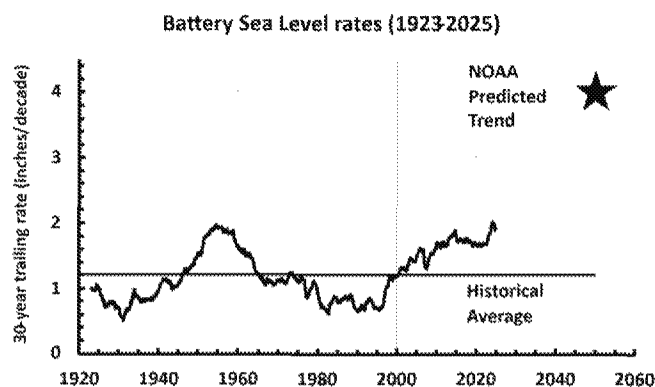
The concern over sea level rise is not about the roughly 8 inches of global rise since 1900. Rather, it is about projections of *accelerated* rise based upon simulations of a warming climate through the 21<sup>st</sup> Century.

The IPCC AR6 finds *high agreement* across published global mean sea level projections for 2050 with little sensitivity to emissions scenarios. Considering only projections incorporating ice-sheet processes in whose quantification there is at least *medium confidence*, the global sea level projections for 2050, across all emissions scenarios, fall between 3.94 and 15.75 inches (5th–95th percentile *very likely* range) relative to the 1995–2014 baseline period (Fox-Kemper et al., 2021).

Conversely, AR6 states there is *low agreement* across published global mean sea level projections for 2100, particularly for higher emissions scenarios. Considering only projections representing ice sheet processes in whose quantification there is at least *medium confidence*, the AR6 global mean sea level projections for 2100 lie between 7.87 and 39.37 inches (5th–95th percentile *very likely* range) under the medium emissions scenario SSP2–4.5 (Fox-Kemper et al., 2021). There is deep uncertainty surrounding projections of sea level rise to 2100, particularly for the higher emissions scenarios.

In evaluating the IPCC AR6 projections to 2050 (with reference to the baseline period 1995-2014), almost half of the sea level rise has already occurred by 2025. From the tide gauge measurements in Figures 7.2-7.5, there is no obvious acceleration in sea level rise beyond the historical average rate of sea level rise.

In February 2022, NOAA issued its projections of sea level rise for various sites along the US coast (Sweet et al, 2022). They claim that by 2050, the sea will have risen one foot at The Battery in Manhattan. A one foot rise in thirty years would be more than twice the current rate and about three times the average rate over the past century. In that historical context, NOAA’s projection is remarkable—as shown in Figure 7.6, it would require a dramatic acceleration beyond anything observed in the early 20<sup>th</sup> century. But even more noteworthy is that they say this rise is “locked in”—it will happen no matter what future emissions are. We should know in a decade or so whether that prediction has legs.



**Figure 7.6** Rate of sea level rise at the Battery in Manhattan. Shown is the historical thirty-year trailing trend, together with the allegedly “locked in” NOAA predicted trend for 2050. Historical data: NOAA Tides and Current.

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## 8 UNCERTAINTIES IN CLIMATE CHANGE ATTRIBUTION

### *Chapter summary*

*“Attribution” refers to determining cause regarding some aspect of climate change, specifically with reference to anthropogenic activity. There is an ongoing scientific debate around attribution methods, particularly regarding extreme weather events. Attribution is made difficult by high natural variability, the relatively small expected anthropogenic signal, lack of high-quality data, and reliance on deficient climate models. The IPCC has long cautioned that methods to establish causality in climate science are inherently uncertain and ultimately depend on expert judgement.*

*Substantive criticism of the main IPCC assessments of the role of CO<sub>2</sub> in recent warming focus on inadequate assessment of natural climate variability, uncertainties in measurement of solar variability and aerosol forcing, and problems in the statistical methods used for attribution.*

*The IPCC does not in general make attribution claims for most climate impact drivers related to extreme events. Statements related to statistics of global extremes (e.g. event probability or return times, magnitude and frequency) are not generally considered accurate owing to data limitations and are made with low confidence. Attribution of individual extreme weather events is challenging due to their rarity. Conflicting claims about the causes of the 2021 Western North America Heatwave illustrate the perils of hasty attribution claims about individual extreme events.*

### 8.1 Introduction

The Intergovernmental Panel on Climate Change (IPCC) distinguishes between detection of climate change and attribution of its cause. As defined by the IPCC AR6 WGI Glossary (IPCC, 2025):

*Detection:* “Detection of change is defined as the process of demonstrating that climate or a system affected by climate has changed in some defined statistical sense, without providing a reason for that change. An identified change is detected in observations if its likelihood of occurrence by chance due to internal variability alone is determined to be small, for example, <10%.”

*Attribution:* “Attribution is defined as the process of evaluating the relative contributions of multiple causal factors to a change or event with a formal assessment of confidence.”

Both steps rely on statistical analysis. Detection focuses on whether changes are significant enough to stand out from random variation regardless of cause. Attribution involves comparison of observed events to model-generated counterfactuals. Since experimentation on the climate is not possible, attribution requires statistical inference to assess how much human activities, such as GHG emissions, versus natural factors, like volcanic eruptions, contribute to observed changes. Attribution methods assume all external and internal drivers of the system are known and represented.

There are ongoing scientific debates around attribution methods, especially those for attributing extreme weather events to climate change. The IPCC has long cautioned that methods to establish causality in climate science are inherently uncertain and ultimately depend on expert judgement. AR4 Working Group I (Hegerl et al., 2007) explained it as follows:

‘Attribution’ of causes of climate change is the process of establishing the most likely causes for the detected change with some defined level of confidence... unequivocal attribution would require controlled experimentation with the climate system. Since that is not possible, in practice attribution of anthropogenic climate change is understood to mean demonstration that a detected change is ‘consistent with the estimated responses to the given combination of anthropogenic and natural forcing’ and ‘not consistent with alternative, physically plausible explanations of recent climate change that exclude important elements of the given combination of forcings’ (IPCC, 2001)... The approaches used in detection and attribution research described above cannot fully account for all uncertainties, and thus ultimately expert judgement is required to give a calibrated assessment of whether a specific cause is responsible for a given climate change.

AR5 Working Group II (Cramer et al., 2014) makes the following statement:

“Two broad challenges to the detection and attribution of climate change impacts relate to observations and process understanding. On the observational side, high-quality, long-term data relating to natural and human systems and the multiple factors affecting them are rare. In addition, the detection and attribution of climate change impacts requires an understanding of the processes by which climate change, in conjunction with other factors, may affect the system in question.”

Because of the complexity of the causal chains in the climate system, investigation of these relationships is exceptionally challenging.

## 8.2 Attribution methods

The IPCC employs several attribution methods to assess the causes of observed climate changes, distinguishing between natural and human-induced factors. Below is a concise description of the key methods that have been used by the IPCC.

*Optimal Fingerprinting* uses linear regression to explain variations in observed climate data as a weighted sum of climate model simulations run with and without anthropogenic forcings. The data used in the regression model are weighted to try to minimize the influence of random noise and the estimation method is chosen to take account of climate model error.

*Time Series Analysis* exploits statistical differences between anthropogenic forcing and natural variability to see which dominates observed temperatures, and also uses variations in the timing of changes to determine if causal dependence across data series can be inferred.

*Process-Based Attribution* focuses on understanding the physical mechanisms behind observed changes. This approach combines observations, climate models, and theoretical understanding to attribute changes in specific processes to forcings. This approach is often used for regional climate phenomena, such as monsoon changes or polar amplification

*Extreme Event Attribution* assesses in the role of human influence in the likelihood of occurrence or intensity of extreme weather events (e.g. heat waves, droughts). Methods include:

- Probabilistic Event Attribution uses large ensembles of climate model simulations to compare observed events to model-generated counterfactuals
- Storyline Approach examines the physical processes driving an event and evaluates how anthropogenic forcings might have modified those processes

### 8.3 Attribution of global warming

Attribution statements for global warming in the three most recent IPCC Assessment reports are:

AR4: “Most of the observed increase in global average temperatures since the mid-20<sup>th</sup> century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations.” (IPCC, 2007)

AR5: “It is *extremely likely* that more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentrations and other anthropogenic forcings together. The best estimate of the human- induced contribution to warming is similar to the observed warming over this period.” (IPCC, 2013)

AR6: “The *likely* range of total human-caused global surface temperature increase from 1850–1900 to 2010–2019 is 0.8°C to 1.3°C, with a best estimate of 1.07°C. It is *likely* that well-mixed GHGs contributed a warming of 1.0°C to 2.0°C, other human drivers (principally aerosols) contributed a cooling of 0.0°C to 0.8°C, natural drivers changed global surface temperature by –0.1°C to +0.1°C, and internal variability changed it by –0.2°C to +0.2°C. It is *very likely* that well-mixed GHGs were the main driver of tropospheric warming since 1979.” (IPCC, 2021)

The AR4 and AR5 attribution statements reference the warming since the mid-20<sup>th</sup> century, the period when greenhouse gas emissions began rapidly increasing. The words “most” and “more than half” are deliberately imprecise, potentially ranging from 51 to 99% of the warming – presumably this imprecision is to account for structural uncertainties such as natural internal variability. The confidence level increases from *very likely* to *extremely likely* from AR4 to AR5. The structure of the attribution statement in the AR6 is fundamentally different, referencing the warming to the period 1850-1900. The AR6 attribution statement is more precise numerically, but with a lower level of confidence at “likely” – the AR6 attributes essentially all the warming to increases in greenhouse gases. The most confident statement from the AR6 relates to the tropospheric warming since 1979, using the words “main driver” and “*very likely*.”

There are three areas of substantive criticism of the IPCC’s assessment of the causes of the recent warming: inadequate assessment of natural climate variability, inappropriate statistical methods, and substantial discrepancies between models and observations. The last is discussed in Chapter 6, while this

chapter discusses the first two factors. All of these criticisms are relevant to the IPCC’s policy-informing attribution of the recent warming, which also underpins extreme event attribution

### 8.3.1 *Natural climate variability*

IPCC AR6 states that natural external drivers since 1850-1900 have changed global surface temperature by  $-0.1^{\circ}\text{C}$  to  $+0.1^{\circ}\text{C}$ , and internal variability has changed it by  $-0.2^{\circ}\text{C}$  to  $+0.2^{\circ}\text{C}$  – on average having essentially no net impact on the warming since 1850-1900. As discussed below, this minimal contribution of natural variability has been disputed by several publications that question the magnitudes of solar variability and internal variability from large-scale ocean circulation.

#### *Solar variability*

IPCC AR5 concluded that the best estimate of radiative forcing due to Total Solar Irradiance (TSI) changes over the period 1750–2011 was very small ( $0.05\text{ W/m}^2$ , Myrhe et al., 2014). IPCC AR6 acknowledges a much larger range of estimates of changes in TSI over the last several centuries, stating that the TSI between the Maunder Minimum (1645–1715) and the second half of the twentieth century increased by  $0.7\text{--}2.7\text{ W/m}^2$ , a range that includes both low and high variability TSI data sets (Gulev, 2021). However, the recommended forcing dataset for the CMIP6 climate model simulations used in AR6 for attribution studies averages two data sets with low solar variability (Matthes, 2017).

While AR6 shows a substantially greater solar impact than does AR5, the overall impact on the climate was still assessed to be small compared to anthropogenic forcing of climate change. However, the impact of solar variations on the climate is uncertain and subject to substantial debate - something that is not evident from the IPCC assessment reports (Lockwood, 2012; Connolly et al., 2021).

The change of TSI over time remains a challenging problem.. Since 1978, there have been direct measurements of TSI from satellites. However, the data exhibits non-negligible inconsistencies, and interpreting any multi-decadal trends in TSI requires comparisons of observations from overlapping satellites. There are several rival composite TSI datasets, disagreeing as to whether TSI increased or decreased during the period 1986–96 (the ACRIM gap; see Chapter 4). Further, the satellite record of TSI is used to calibrate proxy models, whereby past solar variations are inferred from sunspots and cosmogenic isotope measurements (Velasco Herrera et al., 2015).

There is substantial evidence for high solar activity in the second half of the 20<sup>th</sup> century (starting in 1959) and extending into the 1990’s, before a decline in the early 21<sup>st</sup> century; this period is often termed the “Modern Maximum.” (Chatzistergos et al., 2023; Solanki et al., 2004; Usoskin et al., 2007). However, some scientists have concluded that it is not possible to be confident of any multi-decadal trend in TSI (Schmutz, 2021).

This uncertainty causes some reconstructions of TSI from 1750 to have low variability (implying a very low impact of solar variations on global mean surface temperature) whereas datasets with high TSI variability can explain more than 70% percent of the temperature variability since preindustrial times (Scafetta, 2013; Stefani, 2021). The choice of TSI satellite record used in an analysis can therefore substantially influence how much climate change is attributed to human versus natural forcings.

There is growing evidence that other aspects of solar variability, which are referred to as solar indirect effects, either amplify TSI forcing or are independent of TSI forcing. Scafetta et al. (2023) suggests that ~80% of solar influence on climate may stem from non-TSI mechanisms. There are numerous candidate processes, including solar ultraviolet changes; energetic particle precipitation; atmospheric-electric-field effect on cloud cover; cloud changes produced by solar-modulated galactic cosmic rays; large relative changes in the magnetic field; and the strength of the solar wind. Such solar indirect effects are not included

in climate models, although indirect methods of estimating their impacts suggest they are significant. However, claims of non-TSI mechanisms influencing climate are uncertain and debated.

### *Natural variability of large-scale ocean circulations*

Variations in global mean surface temperature are linked to recurrent large-scale variations in ocean circulation patterns, including the Atlantic Multidecadal Oscillation (AMO), the Pacific Decadal Oscillation (PDO) and the El Niño-Southern Oscillation (ENSO). These circulations influence ocean heat uptake and heat distribution, and also influence atmospheric circulation patterns and cloud distributions. There is some debate as to whether these variations are strictly internal to the climate system, or whether this variability can have a solar/astronomical origin or can be influenced by large volcanic eruptions.

While climate models simulate the large-scale ocean circulations and internal climate variability, most models show have too little amplitude compared to observations at multi-decadal frequencies and phasing out-of-sync with the observed climate (Kravtsov et al. 2024). Averaging multiple simulations effectively averages out the internal variations, leaving only the forced climate variability (e.g., CO<sub>2</sub> forcing). With most of the modern warming beginning in the late 1970's, the recent 50-year warming is on the same time scale as the multi-decadal oscillations of the AMO and PDO.

Here are summary statements from the IPCC AR5 and AR6 reports:

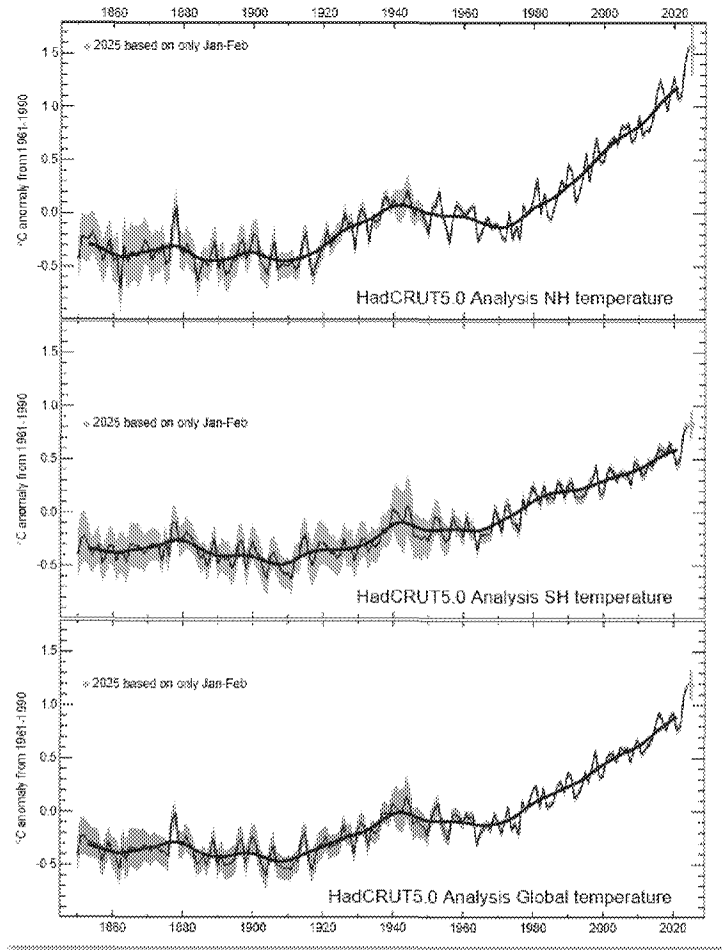
“Decadal variability in the Pacific, associated with the PDO or IPO [Interdecadal Pacific Oscillation], contributes significantly to regional and global temperature trends, but the relative contributions of internal variability and external forcing are difficult to disentangle in CMIP5 simulations.” (IPCC, 2013)

“Since AR5, there has been increased understanding of the role of internal variability, such as ENSO, PDO, and AMO, in modulating regional climate trends. However, limitations in simulating the exact timing and amplitude of these modes in CMIP6 models contribute to uncertainties in attributing observed changes to anthropogenic forcing (*high confidence*).” (IPCC, 2021)

The amplitude of the peak-to-trough impact of the multi-decadal oscillations on global temperatures has been assessed by the IPCC AR6: “The likely range of change due to internal variability is -0.2°C to +0.2°C (IPCC, 2021).” This implies a trough-to-peak change of 0.4°C. Over many centuries, any global temperature changes from the troughs and peaks will cancel out, with little to no net impact.

However, with a nominal timescale of 60-80 years for oscillations such as the AMO and PDO, the timing of the peaks and troughs can be confused with the secular trend. This becomes very relevant for attributing the warming for the past 50 years, when most of the recent warming has occurred. Even if climate models have the correct amplitude of the multidecadal oscillations, the timing of the peaks and troughs is not adequately simulated, with each model and individual ensemble simulating a different phasing. Once the simulations of the ensemble members and different models are averaged, the natural internal variability contribution is averaged out, effectively cancelling the role of natural internal variability in the attribution process.

The time series of global surface temperature anomalies since 1850 (Figure 8.1) shows irregular variations of significant amplitude against the background of an overall warming trend and, after 1976, a pronounced difference in trends between the Northern Hemisphere and the Southern Hemisphere. The period between 1905-1945 shows a strong trend of warming. The following thirty years from 1945-1976 showed slightly declining temperatures. The most recent warming period started in 1977.



**Figure 8.1** Global average surface temperature anomalies 1850—2025. Top: Northern hemisphere. Middle: Southern hemisphere. Bottom: Global average. Source: UK Hadley Centre [ [HYPERLINK "https://crudata.uea.ac.uk/cru/data/temperature/HadCRUT5.0Analysis.pdf"](https://crudata.uea.ac.uk/cru/data/temperature/HadCRUT5.0Analysis.pdf) ]

The causes of the early 20th century warming are discussed by Hegerl et al. (2017; 2019). The atmospheric CO<sub>2</sub> concentration increased from 298 ppm in 1905 to 310 ppm in 1941; hence this implies that CO<sub>2</sub> had little impact on the warming. Volcanic activity during this period was very low, and solar forcing is uncertain. Hegerl et al (2017) somehow inferred that 40-54% of this warming could be attributed to external forcing, with the rest associated with internal variability. Bronniman et al (2024) focused on the causes of the cooling in the first decade of the 20th century in the Southern Hemisphere. They found that the cooling was related to a La-Niña-like pattern in the Pacific, a cold tropical and subtropical South Atlantic, a cold extratropical South Pacific, and cool southern midlatitude land areas. The Southern Annular

Mode was positive, with a strengthened Amundsen–Bellingshausen seas low, although the spread of the data products is considerable.

The warming in the 1930's and subsequent cooling during mid century was particularly pronounced in the Arctic. Bokuchava and Semenov (2021) find that most likely these variations were caused by a combined effect of long-term natural climate variations in the North Atlantic and North Pacific with a contribution of the natural radiative forcing related to the reduced volcanic activity and variations of solar activity as well as growing greenhouse gases concentrations. Tokinaga et al (2017) showed that the combined effect of internally generated Pacific and Atlantic interdecadal variability intensified Arctic warming in the early 20th century. The synchronized Pacific-Atlantic warming drastically alters planetary-scale circulations over the Northern Hemisphere; these same circulation patterns have a global influence.

The cooling period between 1945 and 1976 has been referred to as the “grand hiatus.” Numerous causes have been hypothesized: natural internal variability from fluctuations associated with the Pacific Decadal Oscillation (PDO) and Atlantic Multidecadal Oscillation; cooling from increased emissions of aerosols from industrial activities; increased heat uptake in the Atlantic, Southern and Equatorial Pacific Oceans. Thompson et al. (2010) find that the hemispheric differences in temperature trends in the middle of the twentieth century stem largely from a rapid drop in Northern Hemisphere sea surface temperatures of about 0.3 °C between about 1968 and 1972.

The Great Pacific Climate Shift of 1976-1977 was a notable climatic event characterized by an abrupt change in the North Pacific Ocean's atmosphere-ocean system that interacted with global climate patterns. This shift is closely associated with the Pacific Decadal Oscillation (PDO) that oscillates between warm and cool phases over decades. The 1976 shift marked a transition from a predominantly negative (cool) PDO phase (1947–1976) to a positive (warm) phase (1977 through 2000), with significant implications for global and regional climate patterns including the frequencies of El Nino and La Nina events. The Great Pacific Climate Shift coincided with the beginning of a period of accelerated global warming. When the Great Pacific Climate Shift is accounted for in climate attribution analyses since 1950, 40 percent or more of the warming in the second half of the 20th century is attributed to natural internal variability (McLean et al., 2009; Tung and Zhou, 2013; Chylek et al., 2016; Scafetta, 2021).

### 8.3.2 *Optimal fingerprinting*

Optimal fingerprinting is a statistical technique introduced by Allen and Tett (1999) that compares observed climate data to climate model simulations to identify patterns (or “fingerprints”) associated with human or natural forcing. It involves taking a vector of observed climate changes, such as warming rates in locations around the world, and decomposing them into a weighted sum of “signals”, which are analogues to the observations generated by climate models with different types of forcings. The weights are chosen using a regression method called Total Least Squares. The analysis commonly uses just two signals, one generated by models using only anthropogenic forcings and one using only natural forcings. If the estimated weighting coefficient attached to a signal is significantly different from zero, then that signal is said to be “detected”. If it is close to 1.0, then the model generating the signal is said to be consistent with observations. If it is less than 1.0, then the model signal for that forcing is too strong and needs to be scaled down, and vice-versa. Both the observed data and the signals are weighted using a model-generated estimate of patterns of randomness in the climate system so as, in principle, to put maximum weight on regions where natural variability is minimized.

Optimal fingerprinting is the primary tool for attribution in the research literature. While it has been widely used and prominently featured by the IPCC since 2001 there is very little literature examining the statistical properties of the results it generates. One of its inherent weaknesses is that results depend on assumptions about the accuracy of climate models, especially regarding their representation of natural variability (IPCC AR5 Ch 10.2.3).

A series of papers by McKittrick (McKittrick 2022a, 2022b, 2023, 2025) has challenged the optimal fingerprinting method, arguing that it is inherently unreliable and that practices adopted from econometrics can provide more valid results. Statistical theory requires that for regression models to yield unbiased coefficients, a set of assumptions called the Gauss-Markov conditions must hold. McKittrick (2022a) argued that the Allen and Tett (1999) methodology violates the Gauss-Markov conditions, leading to potentially biased and inconsistent fingerprinting coefficients, undermining the reliability of the method. Chen et al (2023) confirmed this analysis and argued that the method could yield unbiased results but only under very stringent assumptions. McKittrick (2022b) and (2023) raised a further concern that climate scientists—virtually alone among scientific disciplines—have used an estimation method called Total Least Squares (TLS) to estimate anthropogenic greenhouse gas signal coefficients, despite its tendency to be unreliable unless some strong assumptions hold that in practice are unlikely to be true. Under conditions that easily arise in optimal fingerprinting, TLS yields estimates with large positive biases. Thus, any study that used TLS for optimal fingerprinting without verifying its applicability in the specific data context has likely overstated the result.

McKittrick (2025) presented an empirical example comparing the results of conventional optimal fingerprinting against methods drawn from mainstream econometrics that are known to be valid for the specific application of signal detection. While the IPCC optimal fingerprinting method yields an anthropogenic signal coefficient close to 1.0 on a global temperature data set spanning 1900 to 2010, consistent estimation yields a coefficient around 0.4, which rises to about 0.65 on data spanning 1980 to 2010, implying the model response to greenhouse gases needs to be scaled down by about half to optimally match observations. The natural forcing signal coefficient, by contrast, is between 2.0 and 4.0, implying the climate model signals of natural forcing need to be scaled up two-to four-fold to match observed climate change. The fingerprinting coefficients estimated in McKittrick (2025), when used to scale the average sensitivity of the climate models used to generate the forcing signals in his data set, imply a Transient Climate Sensitivity of 1.4°C, which is consistent with the estimate by Lewis (2022) using a different estimation method and multiple independent data sets.

While these analyses do not falsify all results stemming from the IPCC optimal fingerprinting method, they do challenge the basis on which they were believed to be correct.

### 8.3.3 Time series methods

The IPCC (AR5 WGI 10.2.2) drew attention to alternative approaches of assessing causality that emerged from the time series econometrics literature. These have the advantage of not depending on assumptions about the accuracy of climate models, but the disadvantage that they depend on difficult-to-test assumptions about the data generating process underlying climate and forcing data. The methods, now referred to as climate econometrics, use the tools of unit root testing, Granger causality and cointegration analysis, all of which are familiar in economics and finance and which are slowly being adopted in climate science. Time series analysis methods hold out the possibility of determining whether anthropogenic or natural forcings are the primary drivers of climate change without requiring the use of climate models, although key questions remain unsettled (e.g. Dergiades et al. 2016, Balcombe et al. 2019, Dagsvik et al. 2020, Razzak 2022, Dagsvik and Moen 2023).

“Granger causality” modeling is a tool for determining directions of influence in data series that move together. It is a statistical, not a physical, concept. If knowing the current value of one variable significantly improves the forecast accuracy of another variable we can infer a causal connection exists; this is called Granger causality. The modeling tools, called vector autoregression, measure direct impulse-response patterns and feedbacks. An application to the well-known Vostok ice core data revealed an error in Al Gore’s documentary *An Inconvenient Truth*. Gore showed the data and drew attention to the coherence of temperature and CO<sub>2</sub> changes over a 440,000 year span, which he asserted was due to CO<sub>2</sub> driving temperature changes. But temperature changes can also affect atmospheric CO<sub>2</sub> levels. Davidson et al.



(2015) examined the series and found that temperature Granger causes CO<sub>2</sub> but not the reverse. In other words on the time scales represented in the Vostok data the coherence in the series is primarily due to the influence of temperature on CO<sub>2</sub> levels not the feedback of CO<sub>2</sub> levels on temperature.

In summary, the primary statistical methods for attributing causation in climate data are optimal fingerprinting and time series analysis. Applications of the Allen and Tett (1999) optimal fingerprinting method dominate the attribution literature and have underpinned past IPCC conclusions, but results depend on the accuracy of climate models and the method has recently been criticized as inherently biased. Time series methods do not depend on climate models but require assumptions of their own and have generated results that have thus far not converged on a consensus.

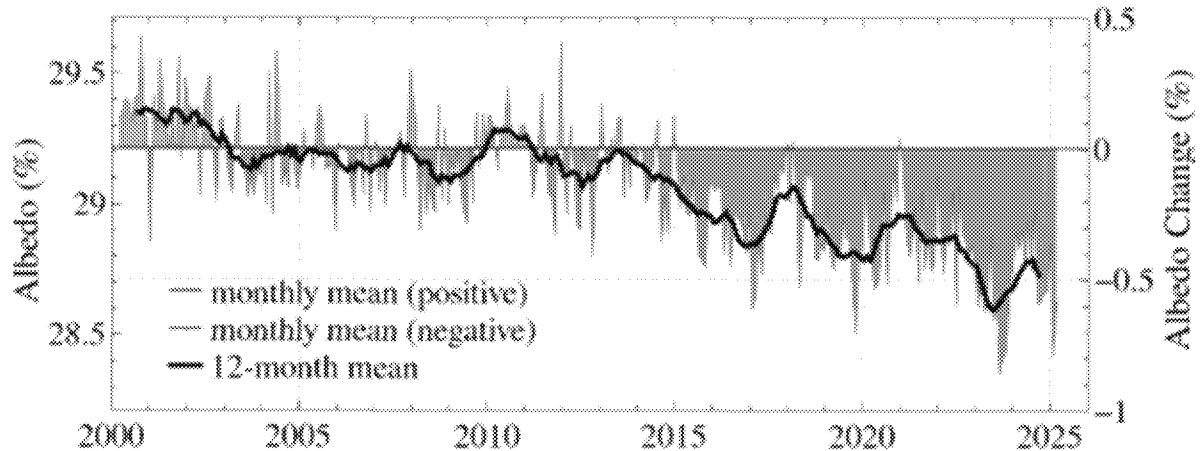
#### **8.4 Declining planetary albedo and recent record warmth**

A sharp recent increase in global average temperatures has raised the question of short-term drivers of climate. One such candidate is the fraction of absorbed solar radiation which has also changed abruptly in recent years. The question to be answered is whether the change is an internal feedback to warming caused by greenhouse gases or whether something else changed the fraction of absorbed radiation which then caused the recent warming.

The albedo is the fraction of incoming solar radiation that is reflected back into space rather than being absorbed by the planet. Highly reflective surfaces like cloud tops and snow and ice are most important in this regard. The Earth's albedo is approximately 30%, meaning almost a third of the sunlight that reaches Earth is directly reflected back to space. A lower albedo implies more solar energy is absorbed by the planet to be then re-radiated as heat. Hence, other things being equal, a decline in albedo is associated with a warming of the Earth.

Arguably the most striking change in the Earth's climate system during the 21<sup>st</sup> century is a significant reduction in planetary albedo since 2015, which has coincided with at least two years of record global warmth. Figure 8.1 shows the planetary albedo variations since 2000, when there are good satellite observations. The 0.5% reduction in planetary albedo since 2015 corresponds to an increase of 1.7 W/m<sup>2</sup> in solar energy averaged over the planet (Hansen and Karecha, 2025). For comparison, the IPCC estimate of forcing from the increase in atmospheric CO<sub>2</sub> compared to preindustrial times is approximately 2.2 W/m<sup>2</sup> (Figure 3.1.2).

Looking back prior to 2000 with less adequate data, Gossling et al. (2025) assessed that planetary albedo was relatively low around the 1940's and 50's, before rising industrial aerosol precursor emissions increased albedo until the 1980's. The strongest planetary albedo excursions were high-albedo episodes caused by volcanic eruptions, such as after the Mount Pinatubo eruption in 1991. Although uncertain, the 2023 planetary albedo minimum may have been the lowest since at least 1940.



**Figure 8.1.** Earth’s albedo (reflectivity, in percent), with seasonality removed. From Hansen and Karecha (2025)

Changes in surface characteristics can’t explain this decrease in planetary albedo since 2015:

- Arctic sea ice extent has declined by about 5% since 1980 ([https://nsidc.org/data/seaice\\_index/images/s\\_plot\\_hires.png](https://nsidc.org/data/seaice_index/images/s_plot_hires.png)), although following 2007 there has been a pause in the Arctic sea ice decline (England et al., 2025)
- Regarding Antarctic sea ice, the IPCC AR6 concludes that “There has been no significant trend in Antarctic sea ice area from 1979 to 2020 due to regionally opposing trends and large internal variability.” (SPM, A.1.5)
- Northern hemispheric annual snow cover has been slowly declining since 1967, with barely significant trends. The data show the Northern Hemisphere has snowier winters, accompanied by more rapid melt in spring and summer.  
[ [HYPERLINK "http://climate.rutgers.edu/snowcover/"](http://climate.rutgers.edu/snowcover/) ]
- Global greening (Chapter 2) is contributing to the decrease in planetary albedo, as forests have a lower albedo than open lands or snow. However, there is some evidence that forests increase cloud cover (high reflectivity), which counteracts the direct albedo increase associated with increasing forested area.

Changes in surface reflectivity are contributing to a small, slow decline in planetary albedo. However, these changes cannot explain the sharp decline in planetary albedo beginning in 2015. Further, any changes in surface albedo are effectively damped by about a factor 3 on average, primarily due to cloud masking (Loeb et al. 2019). Surface albedo changes have thus contributed only weakly to the recent planetary albedo decline, particularly when averaged annually and globally.

This leaves the most likely explanation for the sharp albedo decline as changes in atmospheric aerosols and/or clouds.

Aerosols are small particles in the atmosphere that reflect sunlight and can interact with cloud processes to make the clouds more reflective. Aerosols have both natural origins (e.g dust from soils, wildfires) as well as human origins from combustion (including fossil fuels). Regions that are greening and/or have an increase in rainfall may be producing less dust. For anthropogenic aerosols, new ship fuel regulations aimed at reducing sulfur emissions were implemented in three phases, in 2010, 2015 and 2020. Sulfate

particles reflect solar radiation. Cleaner air means less solar radiation is reflected, which contributes to surface warming. Indirect effects of sulfate aerosols include increasing the reflectivity of low-level clouds in the subtropics. There is controversy surrounding the importance of this change in sulfate emissions to the Earth's radiation balance (Hodnebrog et al., 2024; Yuan et al., 2024), but the restriction of this effect to major shipping routes suggests a small global impact (Schmidt, 2024).

This leaves changes in clouds as the primary candidate to explain the decline in global albedo since 2015. Two recent papers (Loeb et al., 2024; Gosling et al. 2024) have addressed recent variations in cloud properties. By considering satellite and reanalysis data, Loeb et al. found that decreases in low and mid-level clouds since 2015 are the primary reason for decreasing planetary albedo in the Northern hemisphere, whereas in the Southern hemisphere the decrease in planetary albedo is primarily due to decreases in mid-level clouds across all latitude zones. Gosling et al. (2025) found that cloud anomalies were mainly due to reduced low-level clouds. Regions with coherent low-level cloud reductions over the past decade include the warm pool region around the Maritime Continent and the northern extratropical western Pacific, as well as large parts of the Atlantic and adjacent land regions. The reduction of global cloud cover identified in these analyses since 2015 is 1-2 percent.

The question then becomes what caused the change in cloud cover. Two causes have been posited for the declining cloud cover over the past decade:

- Natural climate variability
- Changes in low cloud cover associated with warming sea surface temperatures, implying an emerging positive feedback to climate change (Hansen and Karecha, 2025)

The existence of a new positive low cloud feedback that began emerging in 2015 is not easy to justify. However, there are numerous natural climate signals during this period that are associated with atmospheric circulation changes that can influence the distribution of clouds:

- The 2014-2016 was the strongest El Nino event on record
- A cold anomaly beginning in 2015 in the subpolar gyre of the North Atlantic reflects a shift in the ocean circulation pattern associated with decadal variability in the Atlantic (Frajka-Williams et al., 2017; Arthun et al. 2021).
- The Pacific Decadal Oscillation (PDO) positive index peaked in 2016, then declined and has been in negative territory since late 2019
- Eruption of the submarine Hunga-Tonga volcano in 2022

Interannual cloud anomalies associated with the El Nino Southern Oscillation (ENSO) have a significant global signal and strong regional signals especially over the tropical Indian and Pacific Oceans.

The Hunga Tonga eruption is remarkable in its coincidence with the exceptionally low value of planetary albedo in 2023. Gosling et al. (2025) found that the cloud perturbations in 2023 showed a different pattern from the overall pattern since 2015, with reduced cloud cover being most pronounced in the northern hemisphere and tropics. Regional reductions in cloud cover were most pronounced over the eastern Indian Ocean, over South America and extending over the eastern Pacific, as well as over northern North America, in the Southern Ocean around 60S, in the subtropical and eastern North Atlantic, and in parts of the North Pacific.

The Hunga Tonga eruption was unusual in that it injected large amounts of water vapor into the stratosphere, in addition to sulfate particles. Early publications focused on the impacts to stratospheric circulations and the direct radiative impact. In 2025, papers are emerging that examine the indirect effects of Hunga Tonga on surface climate using ensemble simulations from earth system models (Bednarz et al, 2025; Kuchar et al., 2025). These papers found statistically significant impacts on regional climates that

were driven by circulation changes from couplings between the stratosphere and troposphere. These papers indicate the complex interactions between volcanic activity and climate dynamics. More research is needed to untangle any impacts of Hunga Tonga eruption on planetary albedo.

In summary, the decline in planetary albedo and the concurrent decline in cloudiness have emphasized the importance of clouds and their variations to global climate variability and change. A change of 1 to 2 percent in global cloud cover has a greater radiative impact on the climate than the direct radiative effect of doubling CO<sub>2</sub>. While it is difficult to untangle causes of the trend, the competing explanations for the cause of the declining cloud cover have substantial implications for assessing the Equilibrium Climate Sensitivity and also the attribution of the recent warming. An additional 10 years of data should help clarify whether this is a strong positive cloud feedback associated with warming, or a temporary fluctuation driven by natural variability

## 8.5 Attribution of climate impact drivers

The IPCC (Ranasinghe et al. 2021) defines “climate impact drivers” or CIDs as “physical climate system conditions (e.g., means, events, extremes) that affect an element of society or ecosystems.” Hence CIDs are those features of the weather and climate system of primary interest in assessing the impacts of climate change since they potentially affect humans and the natural world. For instance, under the heading “Heat and Cold” CIDs are identified as mean air temperature, extreme heat, cold spells and frost. The IPCC also points out that CIDs are not necessarily harm-related: depending on the system in question they can be detrimental, neutral, beneficial or a combination.

The first column of Table 12.12 in Ranasinghe et al. (2021, p. 1856), reproduced here as Table 8.1, summarizes the AR6 assessment of whether a signal of attributable anthropogenic influence has emerged across all major CIDs. One of the themes of this chapter is that attribution methods used by the IPCC tend to overstate the anthropogenic influence and understate the role of natural variability. Nonetheless a striking feature of that summary table is how few CIDs exhibit an anthropogenic signal sufficient to distinguish them from natural variability.

| Climatic Impact-driver Type | Climatic Impact-driver Category        | Already Emerged in Historical Period |
|-----------------------------|----------------------------------------|--------------------------------------|
| Heat and Cold               | Mean air temperature                   | 1                                    |
|                             | Extreme heat                           | 2                                    |
|                             | Cold spell                             | 4                                    |
|                             | Frost                                  |                                      |
| Wet and Dry                 | Mean precipitation                     |                                      |
|                             | River flood                            |                                      |
|                             | Heavy precipitation and pluvial flood  |                                      |
|                             | Landslide                              |                                      |
|                             | Aridity                                |                                      |
|                             | Hydrological drought                   |                                      |
|                             | Agricultural and ecological drought    |                                      |
|                             | Fire weather                           |                                      |
| Wind                        | Mean wind speed                        |                                      |
|                             | Severe wind storm                      |                                      |
|                             | Tropical cyclone                       |                                      |
|                             | Sand and dust storm                    |                                      |
| Snow and Ice                | Snow, glacier and ice sheet            |                                      |
|                             | Permafrost                             |                                      |
|                             | Lake, river and sea ice                | 11                                   |
|                             | Heavy snowfall and ice storm           |                                      |
|                             | Hail                                   |                                      |
|                             | Snow avalanche                         |                                      |
| Coastal                     | Relative sea level                     |                                      |
|                             | Coastal flood                          |                                      |
|                             | Coastal erosion                        |                                      |
| Open Ocean                  | Mean ocean temperature                 |                                      |
|                             | Marine heatwave                        |                                      |
|                             | Ocean acidity                          |                                      |
|                             | Ocean salinity                         | 13                                   |
|                             | Dissolved oxygen                       | 14                                   |
| Other                       | Air pollution weather                  |                                      |
|                             | Atmospheric CO <sub>2</sub> at surface |                                      |
|                             | Radiation at surface                   |                                      |

|                             |                               |                                       |                               |                             |
|-----------------------------|-------------------------------|---------------------------------------|-------------------------------|-----------------------------|
| High confidence of decrease | Medium confidence of decrease | Low confidence in direction of change | Medium confidence of increase | High confidence of increase |
|-----------------------------|-------------------------------|---------------------------------------|-------------------------------|-----------------------------|

**Table 8.1:** Reproduction of column 1 of Table 12.12, IPCC AR6 Working Group I report. Emergence of anthropogenic signal in historical period for CIDs shown. White: no signal detected. Blue and orange: change detected (decrease or increase) and confidence level as indicated in color legend.

Out of the 33 weather impact categories an anthropogenic signal is asserted with *high confidence* in only five, and with *medium confidence* in a further four. (Note that one of the CIDs is an increase in CO<sub>2</sub> levels, and since it is a tautology to attribute this to increased CO<sub>2</sub> levels this CID can be ignored.) For the rest the IPCC does not claim to have detected anthropogenic drivers. Of the five *high confidence* assertions, two are for changes in average temperatures (air and ocean) hence are not measures of extreme weather. Also two of the four *medium confidence* assertions are related to ocean chemistry and thus are likewise not related to extreme weather. The IPCC does not assert a human influence on many non-temperature weather features such as wind, precipitation, flooding, drought etc.

Columns 2 and 3 of IPCC Table 12.12 report on whether anthropogenic signals are expected to emerge this century under RCP8.5, the most extreme forcing scenario. We have omitted these columns for several reasons. First, because they refer to whether climate models project detectable signals in the observations, which is a very different question than our concern here, whether a signal has been detected in historical data. Second, as we discuss in Chapter 4, the RCP8.5 scenario is a misleading and implausible high-end storyline, it is not a “base case” or business-as-usual projection. Third, the ensemble of detailed models is acknowledged (Palmer and Stevens 2019) to be “not fit for purpose” in describing regional changes and “unable to represent future conditions at the degree of spatial, temporal, and probabilistic precision with which projections are often provided.” (Nissan et al, 2019) Even with these caveats, we note that the omitted columns in AR6 Table 12.12 indicate most weather impacts are not expected to exhibit an anthropogenic signal this century.

As we discussed in Chapter 7 natural variability dominates patterns of extreme weather systems and simplistic assertions of trend detection are frequently undermined by regional heterogeneity and trend reversals over time. Table 8.1 makes the related point that, again contrary to popular belief, attribution of changes in most extreme weather types to human influence is not currently possible. Taking wind as an example, the IPCC claims that an anthropogenic signal has not emerged in average wind speeds, severe windstorms, tropical cyclones or sand and dust storms, nor is one expected to emerge this century even under an extreme emissions scenario. The same applies to drought and fire weather.

## 8.6 Extreme event attribution (EEA)

Examining the IPCC’s treatment of extreme weather and climate event attribution more broadly, the AR6 provides an ambiguous assessment of the role of anthropogenic warming that differs between chapters. Chapter 11 of WG1 states (Seneviratne et al., 2021):

“Evidence of observed changes in extremes and their attribution to human influence (including greenhouse gas and aerosol emissions and land-use changes) has strengthened since AR5, in particular for extreme precipitation, droughts, tropical cyclones and compound extremes (including dry/hot events and fire weather). Some recent hot extreme events would have been extremely unlikely to occur without human influence on the climate system.”

By contrast, as noted above, Chapter 12 of WG1 (Table 12.12) paints a different picture – presumably, the expert judgment of different groups of authors for the two chapters came to different conclusions (Ranasinghe, 2021):

- High confidence in an increase in extreme heat events in tropical regions where observations allow trend estimation and in most regions in the mid-latitudes, medium confidence elsewhere

- Medium confidence in a decrease in extreme cold events in Australia, Africa and most of northern South America where observations allow trend estimation
- No evidence of emergence in the historical period of a change in river floods, heavy precipitation, drought, fire weather, severe wind storms, and tropical cyclones

While the overall issue of detecting changes in extreme weather events and their attribution remains ambiguous, most of the activity in this area relates to the attribution of particular extreme weather events. The most prominent effort is World Weather Attribution (WWA; [worldweatherattribution.org](http://worldweatherattribution.org)), an international research initiative for extreme event attribution that purports to analyze how climate change influences the likelihood and intensity of extreme weather events. Their approach is to use large ensembles of regional climate models to compare the event in today's climate with a counterfactual pre-industrial climate without human influences.

WWA has a prominent public presence in linking extreme weather to climate change, with its press releases attracting considerable attention in public and policy discussions. However, the WWA's extensive promotion of non-peer-reviewed findings, its funding ties, its open admission to shaping analyses to serve litigation, and its methodological challenges have sparked controversies, with critics questioning the robustness and impartiality of their conclusions (Pielke Jr. 2024). Despite these issues, WWA's work continues to influence climate science and media narratives. Technical criticisms of the approach include a lack of a formal detection process; an implicit assumption that 100% of the post-industrial warming is caused by greenhouse gases; and a failure to adequately account for internal climate variability.

Because EEA is relatively new many basic methodological issues have yet to be settled in the expert literature. An important challenge is the lack of data. Extreme events are by definition rare. Many analyses of extreme event types (including the US National Assessment Reports) only evaluate data since 1950 or 1970. However, as emphasized by Chapter 7, many of the worst extreme weather and climate events in U.S. history occurred prior to the first half of the 20<sup>th</sup> century including in the early 19<sup>th</sup> century. And if paleoclimate reconstructions are considered, it becomes very difficult for an event to pass the detection thresholds of exceeding what is expected from natural variability, particularly if a reasonably sized geographic region is considered.

Another challenge is defining the event under study. There is a longstanding literature in statistics and econometrics on the challenge of analyzing data with outliers. The issue arises because a data series establishes a probability distribution defining the expected range of observations. If an outlier is observed it might indicate that the underlying process giving rise to the data distribution has changed (which in the weather context would mean that a climate change has been detected) or that the underlying process has multiple regimes each with a different probability distribution, in which case observing an outlier simply means we were temporarily in a different regime, but the system itself was unchanged. If a time series contains only a single outlier event at the end of the series it is not possible to determine which model is the correct one (Chen and Liu 1993). For instance, there might be an "ordinary" weather regime that yields a distribution of summer daytime highs in a particular coastal region, and a second "heatwave" regime that kicks in when an inland blocking event occurs, which yields a temperature distribution centered 15°C higher than the first one. A day with temperatures 13°C above normal would either be an extreme heat anomaly under the first regime or a somewhat cool event under the second, and we have no way in this case of knowing on statistical grounds which view is correct.

Visser and Petersen (2012) and Sardeshmukh et al. (2015) both point out that different distributions may fit observed data equally well but yield very different implications about the likelihood of a specific weather event. Visser and Petersen argue that, in view of the deep uncertainties of extreme weather analysis drawing a connection between individual events and global climate change should be avoided. Furthermore, the existence of an outlier at the end of a data series poses the problem that estimates of the event probabilities will be biased whether the outlier is included or excluded (Barlow et al. 2020). Methods to

eliminate the bias have not yet been established, leading some experts (e.g. Miralles and Davison 2023) to argue that in settings in which a data series contains a single extreme event at the end, estimation of a return period for the extreme event will be so biased and uncertain it should be avoided altogether.

In spite of these concerns, the U.S. is presently considering something like the WWA, which is being investigated by a NASEM Panel on Attribution of Extreme Weather and Climate Events and their impacts (NASEM, 2025).

We provide a case study of a recent high impact extreme event in the U.S. to illustrate the challenges and ambiguities in attributing the frequency and intensity of extreme weather events to human-caused warming.

#### *8.6.1 Case study – 2021 Western North America heat wave*

The 2021 Western North America heat wave was an extreme event that affected much of Western North America in late June 2021. In particular, surface temperature records were set in Portland, OR (116°F; previous record 107°F) and Seattle, WA (108 °F; previous record 103°F) (Mass et al., 2024).

The WWA team generated international headlines with their analysis, which provided the following attribution statements (WWA, 2021; Philip et al., 2022):

- Based on observations and modeling, the occurrence of this heatwave was virtually impossible without human-caused climate change.
- The event is estimated to be about a 1 in 1000-year event in today’s climate.
- The event would have been at least 150 times rarer without human-induced climate change.
- This heatwave was about 2°C hotter than it would have been if it had occurred at the beginning of the industrial revolution (when global mean temperatures were 1.2°C cooler than today).

But an important counter to the first claim is that other researchers concluded from historical weather data that while a heat wave of the magnitude observed was indeed virtually impossible without anthropogenic climate change, it was also virtually impossible *with* climate change. Bercos-Hickey (2022) noted “these temperatures were virtually impossible under any previously experienced meteorological conditions, with or without global warming.” McKinnon and Simpson (2022) stated “the most likely explanation remains that the weather event itself was ‘bad luck.’” The 2023 Oregon Climate Assessment (Fleischman 2023) concluded that the heat dome would have formed even without climate change and “There is no evidence that the highly unusual combination of weather features that drove the heat dome were made more likely by climate change, and climate models do not project an increase in the frequency of high-pressure ridges over the Pacific Northwest” (Fleischman 2023 p. 49).

Mass et al. (2024) summarizes the proximate sequence of compound events leading to the heat wave. There was a record-breaking mid-tropospheric ridge over the Pacific Northwest, forced by a tropical disturbance in the western Pacific. This produced record-breaking mid-tropospheric temperatures, strong subsidence in the lower atmosphere, low-level easterly flow that produced downslope warming on regional terrain and the removal of cooler marine air, and an approaching low-level trough that enhanced downslope flow. The event occurred at a time of maximum solar insolation, and drier-than-normal soil moisture. Using a storyline approach, Mass et al. assessed that there is no trend in drought and dry soils in the Pacific Northwest; there is no evidence of global warming producing stronger ridges of high pressure, and no observed trend in heat waves or record temperatures in the region. They concluded that although anthropogenic warming may have contributed as much as 2°F to the magnitude of the event, there is little evidence of further amplification of the event from increasing greenhouse gases.



Bercos-Hickey et al. (2022) conducted a statistical analysis of a model-based attribution study of this heat wave. Because the event is a far outlier and far above the bounds of Generalized Extreme Value distributions fitted from historical data, they concluded that estimates of return times, quantitative changes in event magnitude and frequency, and probability of the extreme temperatures such as provided by the WWA are not accurate and should be interpreted as having low confidence. They found that hindcast attribution methods using an ensemble of regional climate models, combined with Pearl (2009) causal inferences, can provide limited and conditional information about the magnitude of the human influence on this heatwave - they provided a more highly constrained estimate that human activities caused a  $\sim 1.4^{\circ}\text{C}$ – $1.8^{\circ}\text{F}$  increase in the daily maximum temperatures.

Zeder et al. (2023) also concluded that the methods employed by Philip et al. (2022, the WWA analysis) tend to overstate the rarity of extreme heat waves, leading to a biased perception of the effect of climate change on the heatwave event: “The tendency to overestimate the return period of observed extreme heatwave events may fuel the impression that seemingly impossible heatwave extremes are currently clustering at an unprecedented rate.”

The 2021 Western North America heatwave was a rare and unprecedented compound weather event that broke century-old temperature records by as much as  $9^{\circ}\text{F}$ . While the WWA team received worldwide publicity for their rapid attribution claims blaming anthropogenic climate change, subsequent peer-reviewed analyses showed that the event was caused by rare meteorological conditions that were not made more probable by global warming.

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## **PART III: IMPACTS ON ECOSYSTEMS AND SOCIETY**



## 9 CLIMATE CHANGE AND US AGRICULTURE

### Chapter summary

*There is abundant evidence going back decades that rising CO<sub>2</sub> levels benefit plants, including agricultural crops, and that CO<sub>2</sub>-induced warming will be a net benefit to US agriculture. The warming since 1981, in combination with adaptive behavior by farmers, has been beneficial for maize. The increased ambient CO<sub>2</sub> has also boosted productivity of all major US crop types. Various attempts to argue that CO<sub>2</sub>-induced warming will harm agriculture do not hold up under scrutiny.*

### 9.1 Econometric analyses

Econometric analyses of the effects of climate change on agriculture have sought to integrate information about long term crop yield changes in response to temperature and precipitation changes under assumptions about adaptive behavior by farmers. One method focuses on variations in agricultural land values. The rationale is that if climate change is a long-term net benefit for agriculture it should be capitalized into higher market values for agricultural land, and vice versa. While individual crops might benefit from or be harmed by climate change, once the adaptive responses of farmers are considered the value of farmland represents an index of whether the changes are expected to be beneficial or not. Mendelsohn et al. (1994) examined the relationship between historical climatic variations on agricultural land values and concluded global warming would be slightly beneficial to American agriculture.

The Mendelsohn et al. method, called Ricardian analysis after David Ricardo, the 19<sup>th</sup> century British economist who pioneered the study of land values, attracted subsequent criticism from authors who argued it failed to account for differences in land values attributable to fixed locational characteristics like soil quality, and non-climatic changes including nearby urbanization. Deschênes and Greenstone (2007) looked at agricultural profits instead of land values and reached conclusions similar to Mendelsohn et al. (1994), namely that past climatic variations had relatively little effect on farm profitability and that warming would likely yield small overall benefits for the US agricultural sector. However, a subsequent exchange with critics led them (Deschênes and Greenstone 2012) to revise their conclusions and project potentially large losses in US agriculture due to climate warming.

Burke and Emerick (2016) looked at temperature variations over 1980 to 2000 and argued that farmers were not as able to adapt to temperature changes as the Ricardian method assumes and that climate change would have large negative impacts on corn and soy yields. Schlenker and Roberts (2009) similarly argued that yield gains to past warming would not carry over to the future and corn and soy yields would sharply decrease this century due to climate change.

Two recent studies have argued that pessimistic findings such as these are not robust. Ortiz-Bobea (2019) argued that land values aggregate farm and non-farm influences and the latter need to be filtered out. He developed a data set using cash rents for agricultural activity as a measure of land value specifically for farming activity. Whereas the land value model implied future losses under climate warming, the same model estimated using cash rents did not, leading the author to conclude the pessimistic results were due to using an inaccurate measure of the returns to farming activity. Bareille and Chakir (2023) assembled a large data base on farm sale prices in France for properties that sold twice between 1996 and 2019. They could replicate pessimistic results showing negative effects of warming on agricultural land values using conventional econometric modeling. But by taking advantage of the repeat sales data, which provides

information on site-specific changes in land prices, they found the results reversed and implied that climate change will be very beneficial for French agriculture. The authors concluded that, taking adaptation into account, a warming climate would yield positive benefits for French agriculture that were between two and 20 times larger than had previously been estimated. On average, with full adaptation, they concluded that climate changes under the medium RCP4.5 scenario could double the value of French farmland by 2100.

A major deficiency of all these studies, however, is that they omit the role of CO<sub>2</sub> fertilization. Climate change as it relates to this report is caused by GHG emissions, chiefly CO<sub>2</sub>. The econometric analyses referenced above focus only on temperature and precipitation changes and do not take account of the beneficial growth effect of the additional CO<sub>2</sub> that drives them. As explained in Chapter 2 CO<sub>2</sub> is a major driver of plant growth, so this omission biases the analysis towards underestimation of the benefits of climate change to agriculture.

## 9.2 Field studies of CO<sub>2</sub> enrichment

One of the ways the effect of CO<sub>2</sub> on crop growth has been studied is through “free air enrichment experiment” or FACE plots, in which small sources of CO<sub>2</sub> are placed in fields surrounding plants and the growth response to elevated CO<sub>2</sub> under varying weather conditions are recorded. Ainsworth et al. (2020) summarizes results from about 250 such studies. They found that elevation of CO<sub>2</sub> by 200 ppm caused an average 18% increase in crop yield in C3 plants. C4 plants exhibited benefits mainly under drought conditions.

In addition to FACE plot experiments there have been thousands of laboratory experiments on the effects of CO<sub>2</sub> on all kinds of plant growth. Here we review some of the results on key US agricultural crops.

### *Soybean*

Studies on the impact of elevated CO<sub>2</sub> on Soybean (*Glycine max* (L.) Merr.) plants in the water-deficient region of Huang-Huai-Hai Plain, China, showed that elevated CO<sub>2</sub> concentrations improved photosynthesis rate, water use efficiency, and growth (Li, 2013) under both normal conditions and drought conditions. The CO2Science.org website reports on 108 published experiments between 1985 and 2019 exposing soybean to enriched CO<sub>2</sub> levels. Converted to a +300ppm common scale the average growth benefit was +50.9 percent. There were also ten studies reporting on +600 ppm CO<sub>2</sub> enrichment, which increased photosynthesis by an average of 90.3%.

### *Maize (corn)*

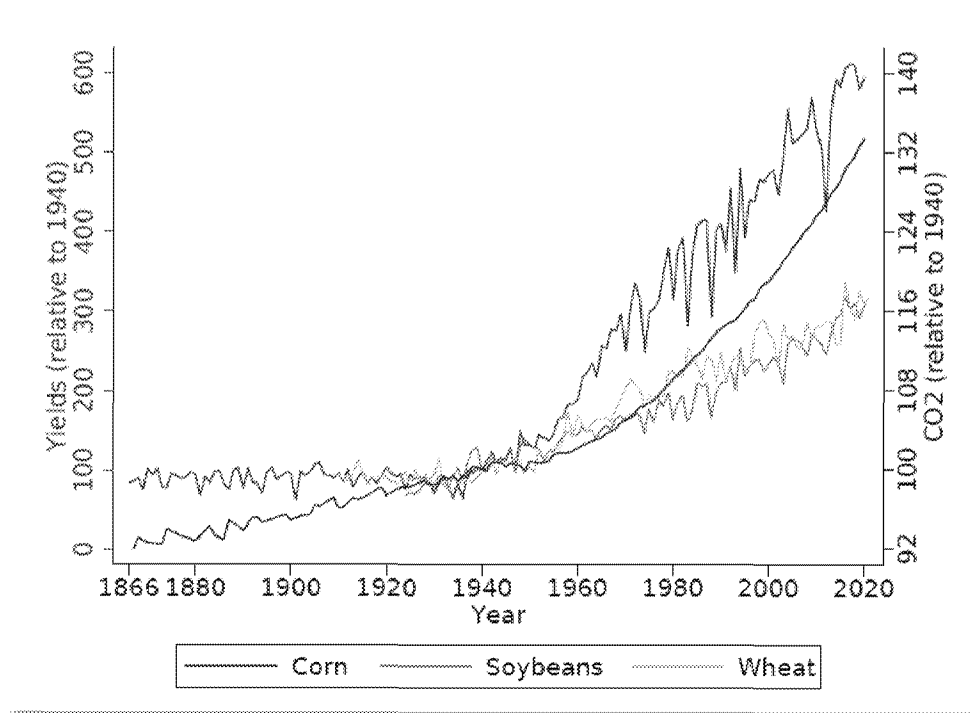
The CO2Science.org website reports on 28 published experiments between 1983 and 2018 exposing corn (*Zea mays* L.) to enriched CO<sub>2</sub> levels. Converted to a +300ppm common scale the average growth benefit was +23.7 percent. Corn also benefits from increased drought tolerance under elevated CO<sub>2</sub>. An experimental study (Allen Jr, 2011) exposed plants to water stress conditions in sunlit controlled-environment chambers at 360 ppm (ambient) and 720 ppm (elevated) CO<sub>2</sub>. The drought stress caused a 41% loss of growth under ambient CO<sub>2</sub> but only a 13% loss under elevated CO<sub>2</sub>.

### *Wheat*

The CO2Science.org website reports on 92 published experiments between 1983 and 2020 exposing common wheat (*Triticum aestivum* L.) to enriched CO<sub>2</sub> levels. Converted to a +300ppm common scale the average growth benefit was +67.6 percent. Blandino (2020) measured both the yield and nutritional quality of an “improver” hybrid wheat variety and its parents under elevated CO<sub>2</sub> levels (+166 ppm). They reported a grain yield increase of +16% but a 7% decrease in grain protein levels. But they found that the food quality of different wheat varieties responded differently to elevated CO<sub>2</sub> levels, so that with proper varietal selection, growers could select wheat types that best take advantage of the elevated CO<sub>2</sub>.

#### *Further evidence*

A 2021 report from the US National Bureau of Economic Research (Taylor and Schlenker 2021) used satellite-measured observations of outdoor CO<sub>2</sub> levels across the United States, matched to county-level agricultural output data and other economic variables. After controlling for the effects of weather, pollution and technology the authors concluded that CO<sub>2</sub> emissions had boosted U.S. crop production since 1940 by 50 to 80 percent, attributing much larger gains than had previously been estimated using FACE experiments. They found that every ppm of increase in CO<sub>2</sub> concentration boosts corn yields by 0.5 percent, soybeans by 0.6 percent, and wheat by 0.8 percent.



**Figure 9.1:** US average CO<sub>2</sub> levels and yields of corn, soy and wheat all normalized so 1940=100.  
Source: Taylor and Schlenker (2021)

Beyond growth benefits, extra CO<sub>2</sub> boosts plant resilience to dryness. Derying et al. (2016) surveyed evidence on crop water productivity (CWP, the yield per unit of water used), drawing attention to the potential for CO<sub>2</sub> both to enhance photosynthesis and reduce leaf-level transpiration (water loss during leaf respiration). They surveyed all available FACE data on crop yield changes for Maize (corn), Wheat, Rice

and Soybean, and combined it with crop model data simulating yield responses as of 2080 under the extreme RCP8.5 scenario in four growing regions (Tropics, Arid, Temperate and Cold) each of which were split into rainfed and irrigated sub-regions. In every region they reported that models without CO<sub>2</sub> fertilization predicted CWP losses but CO<sub>2</sub> fertilization more than offset them; once fertilization was taken into account, all regions showed a net CWP gain. Deryng et al. also reported that negative yield impacts on wheat and soybean were fully offset by CWP gains, and mitigated by up to 90% for rice and 60% for maize.

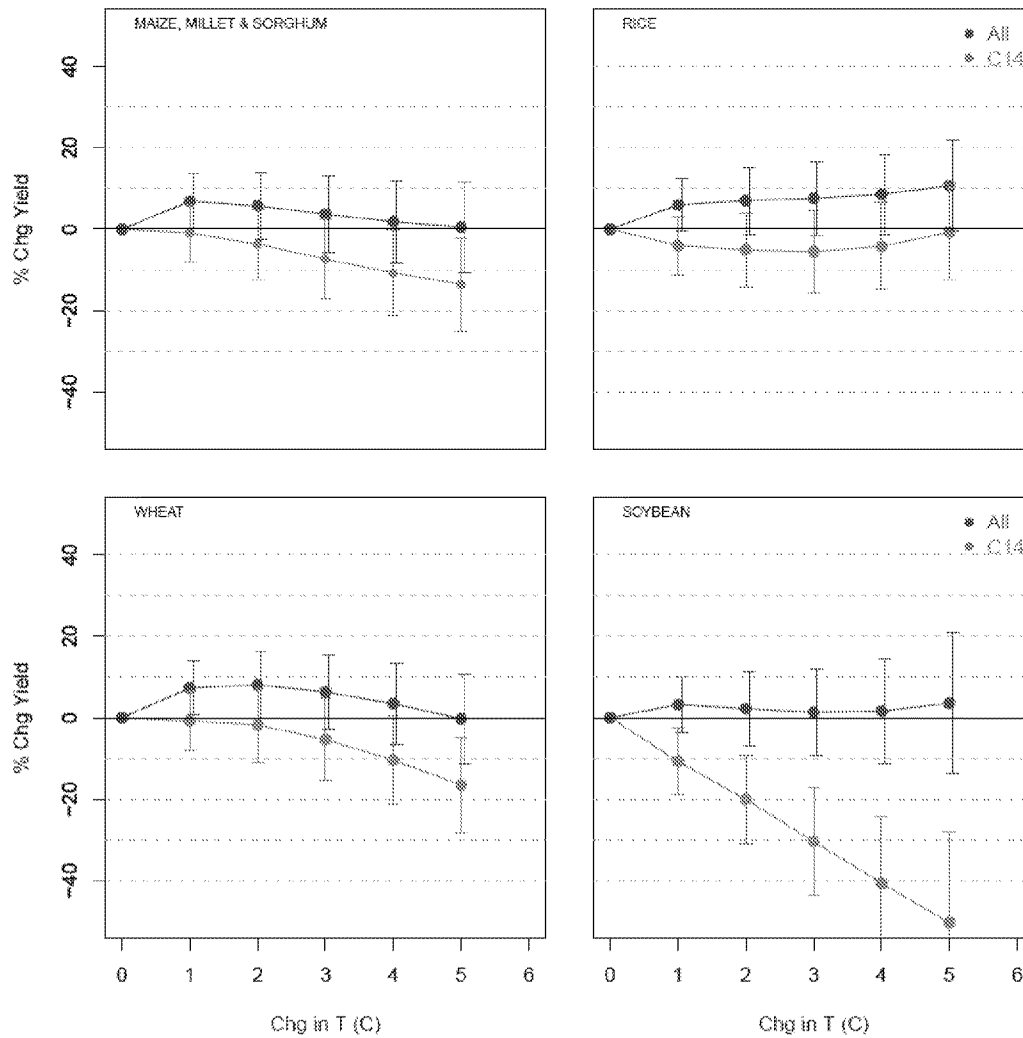
Similar to this, Cheng et al. (2017) noted that increased global plant growth from 1982 to 2011 due to rising CO<sub>2</sub> uptake was accompanied by such large gains in CWP that despite the extra biomass global water use by plants had not increased.

Deryng et al. (2016) assumed that climate change would “exacerbate water scarcity”. It is noteworthy that while models predict drylands will expand under climate warming, observations show the opposite: greening is happening even in arid areas. Zhang et al. (2014) report that due to increased CO<sub>2</sub> levels “increasing aridity in drylands won’t lead to a general loss of vegetation productivity”; increased desertification will happen in at most 4% of currently arid areas.

### 9.3 Crop modeling meta-analyses

Notwithstanding the abundant evidence for the direct benefits of CO<sub>2</sub> and of CO<sub>2</sub>-induced warming on crop growth, in 2023 the US Environmental Protection Agency (EPA 2023) boosted its estimate of the Social Cost of Carbon (SCC) about five-fold based in large part on a very pessimistic 2017 estimate of global agricultural damages from climate warming (Moore et al., 2017). One of the two damage models used by the EPA attributed nearly half of the 2030 SCC to projected global agricultural damages based on the Moore et al. (2017) analysis. This study was a meta-analysis of crop model studies simulating yield changes for agricultural crops under various climate warming scenarios. Moore et al. projected declining global crop yields for all crop types in all regions due to warming.

McKittrick (2025) re-examined the Moore et al. database and found that, while it claimed to cover 1,722 studies, only half the entries ( $N=862$ ) had complete records, so that the sample available for regression analysis was much smaller than both studies indicated. McKittrick noted that the variable most commonly missing was the change in ambient CO<sub>2</sub> and found that in many cases these could be recovered from the underlying studies or the original climate scenario tables. He thereby increased the usable sample size by 40 percent. The crop yield projections incorporating the newly available data changed considerably. As shown in Figure 10.2, whereas the partial data set implied warming would decrease yield (blue lines), the complete data set implied constant or increase global yields, even out to 5°C warming (green lines).



**Figure 9.2** Crop yields under CO<sub>2</sub>-induced climate warming. Blue: as published in Moore et al. (2017). Green: after including omitted data. Source: McKittrick (2025).

In summary, there is abundant evidence going back decades that rising CO<sub>2</sub> levels benefit plants including agricultural crops, and that CO<sub>2</sub>-induced warming will be a net benefit to US agriculture.

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## 10 MANAGING RISKS OF EXTREME WEATHER

### Chapter summary

*Trends in losses from extreme weather and climate events are dominated by population increases and economic growth. Technological advances such as improved weather forecasting and early warning systems have substantially reduced losses from extreme weather events. Better building codes, flood defenses, and disaster response mechanisms have lowered economic losses relative to GDP. The US economy's expansion has diluted the relative impact of disaster costs, as seen in the comparison of historical and modern GDP percentages. Heat-related mortality risk has dropped substantially due to adaptive measures including the adoption of air conditioning, which relies on the availability of affordable energy. U.S. mortality risks even under extreme warming scenarios are not projected to increase as long as people are able to undertake adaptive responses.*

### 10.1 Socioeconomic context

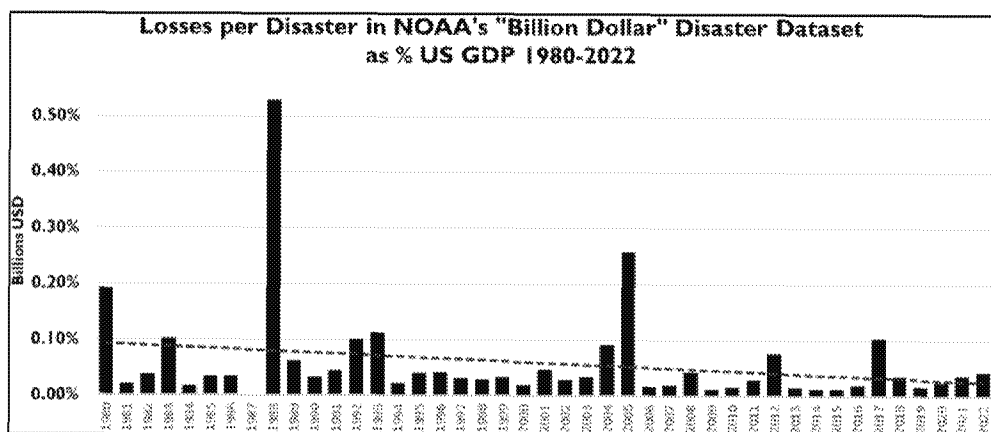
Risks from human-caused climate change are affected by natural weather and climate variability, and are dominated by the exposure of wealth in coastal and other disaster-prone regions and vulnerabilities of poorer populations. The evolution of climate risk in the U.S. has been dominated by societal factors, rather than by changes to the actual weather and climate hazards. Deaths from weather disasters have decreased substantially since 1900, even as US population grew from 76 million in 1900 to over 331 million in 2020 (Goklany, 2011). For example, the Galveston hurricane killed over 8,000 people in 1900 (0.01% of the US population), whereas the worst recent disaster, Hurricane Katrina in 2005, killed 1800 people (or 0.0006% of the US population) (NOAA, 2025; USCB, 2025).

Technological advances have substantially reduced losses from extreme weather events. Early warning systems, satellite monitoring, and improved weather forecasting have reduced deaths, although exact numbers are hard to quantify (Deryugina and Hsiang, 2023). US weather forecasting has been estimated to reduce losses from weather events with an annualized benefit of \$31.5B, protecting lives, property, and supporting agriculture and transportation (NRC, 2010). Improved hurricane forecasts have reduced pre- and post-landfall spending, with annual per hurricane cost reductions estimated at \$5B (NBER, 2024).

Infrastructure improvements have contributed to substantial reductions in losses from extreme weather events. Building codes, such as those implemented in Florida after Hurricane Andrew (1992) have reduced losses by ensuring structures can withstand high winds and floods. Homes built after 2002 showed minimal damage during Hurricane Michael (2018), unlike older homes (FEMA, 2020). Sea walls, like the Galveston Seawall, protect against wave action and storm surge. The New Orleans Hurricane and Storm Damage Risk Reduction System successfully mitigated storm surge during Hurricane Isaac (2012) (BMI, 2013). Inland dams in the US help control flooding by storing excess water during heavy rains. It is estimated that the Tennessee Valley Authority (TVA) dams prevent about \$309M in annual flood damage in the TVA region and along the Ohio and Mississippi Rivers (TVA, 2025). During Hurricane Helene (2024), TVA's strategies prevented approximately \$406M in potential damages (APPA, 2024).

### 10.2 Data challenges

Since 1980, NOAA has provided a count of annual U.S. weather-related disasters that it estimates to have exceeded \$1Billion (inflation adjusted), showing a substantial increase starting in 2008. NOAA and other government officials have cited the upward trend in the Billion Dollar Disaster series as evidence that climate change is making extreme weather worse (Pielke Jr., 2024). But over time, population and wealth have increased dramatically in the US, so when an extreme weather or climate event occurs, there is more damage even if there is no underlying trend in the frequency or intensity of extreme weather. Pielke Jr. (2024) demonstrates that losses per weather disaster as a proportion of GDP have decreased by about 80% since 1980, as shown in the figure below. Pielke Jr. (2024) also argued that in addition to relying on opaque data sources and unreported adjustments, NOAA failed to normalize its Billion Dollar Disaster data series properly for changes in population exposure and wealth. In May 2025 NOAA announced it has withdrawn the Billion Dollar Disaster product from publication (Pielke Jr., 2025).



**Figure 10.1:** Losses per disaster in NOAA’s billion dollar disaster dataset (the version downloaded in July 2023), 1980 to 2022. Source: (Pielke, Jr. 2024)

In summary, trends in losses from extreme weather and climate events are dominated by population increases and economic growth. Technological advances such as improved weather forecasting and early warning systems have substantially reduced losses from extreme weather events. Better building codes, flood defenses, and disaster response mechanisms have lowered economic losses relative to GDP. And finally, the US economy's expansion has diluted the relative impact of disaster costs, as seen in the comparison of historical and modern GDP percentages.

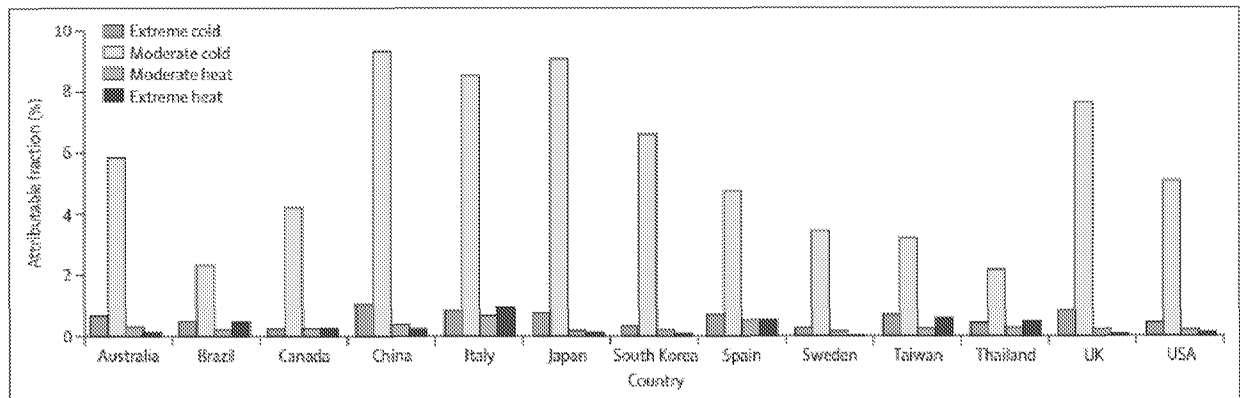
### 10.3 Mortality from temperature extremes

#### 10.3.1 Heat and cold risks

Changes in temperature extremes are among the most certain impacts expected in a warming world. It stands to reason that extreme heat events would likely become more frequent while extreme cold events would become less frequent. This pattern is evident in the historical period though not in the continental US (Chapter 6) and is expected to continue with further warming.



Mortality during heat extremes is typically caused by heat stroke and heat exhaustion, while mortality during cold extremes is typically caused by hypothermia and heart strain. Global mortality is substantially greater for cold conditions than for hot conditions (Zhao et al 2021, Ritchie 20214). Unlike with heat-related mortality. Cold-weather risks set in even at moderately cold conditions (Gasparini et al. 2015, Lee and Dessler 2023). A 13-country study of 74 million deaths from 1985 to 2012 estimated that, on average, 7.7% of deaths were attributable to sub-optimal temperatures, of which 7.4% were attributable to cold and only 0.4% were attributable to heat (Gasparini et al. 2015). In other words cold weather killed 18.5 times as many people as did hot weather.



**Figure 10.3.1.** Mortality attributable to extreme and moderate cold and heat by country. Source: reproduced from Gasparini et al. (2015).

Figure 10.3.1 shows the distribution of results from Gasparini et al. (2015) by country. For the United States the fraction of deaths attributable to temperature was 5.9%, of which 5.5% was due to cold, thus cold weather killed 14 times as many people as hot weather.

The US EPA reports that, after adjusting for seasonality, the cold-related death rate in the U.S. is about twice as large as the heat-related rate (see [ [HYPERLINK "https://www.epa.gov/climate-indicators/climate-change-indicators-cold-related-deaths"](https://www.epa.gov/climate-indicators/climate-change-indicators-cold-related-deaths) ] and ([ [HYPERLINK "https://www.epa.gov/climate-indicators/climate-change-indicators-heat-related-deaths"](https://www.epa.gov/climate-indicators/climate-change-indicators-heat-related-deaths) ])).

There is strong evidence that people adapt to weather risks. Lee and Dessler (2023) reported that 86% of temperature-related deaths across 40 cities in the U.S. were due to cold-related mortality, and that due to adaptation the relative risk of death declined in hot and cold cities alike as seasonal temperatures increased. Allen and Sheridan (2018) found that short, early-season cold events were 2 to 5 times deadlier than hot events, but the mortality risk of both cold and hot extremes drops to nearly zero if the events occur late in the season.

Davis et al. (2003) examined heat-related mortality in 28 U.S. cities from the 1960s to the end of the 1990s and found that heat-related mortality declined by three-quarters over the sample period. Bobb et al. (2014) examined mortality data for 106 million people in over 100 cities U.S. cities and found a 60% decline in average heat-related mortality over the period 1987—2005, from 51 per thousand deaths to 19. They furthermore found that the greatest drop was among seniors over the age of 75. In a study of 42 million deaths in 211 U.S. cities from 1962 to 2006. Nordio et al. (2015) found a more than 90 percent decline in the risk of mortality from excess heat.

In the context of large declines in heat-related mortality, by reducing mortality from cold events rising temperatures are associated with a net saving of lives.

The IPCC AR6 Working Group 2 Chapter 16.2.3.5 (O'Neill et al. 2022) acknowledges that heat-related mortality risk is declining over time:

“Heat-attributable mortality fractions have declined over time in most countries owing to general improvements in health care systems, increasing prevalence of residential air conditioning, and behavioral changes. These factors, which determine the susceptibility of the population to heat, have predominated over the influence of temperature change.”

It is both disappointing and telling to see how the IPCC misrepresents the situation in its AR6 Synthesis report. Section A.2.5 of that document states: “In all regions increases in extreme heat events have resulted in human mortality and morbidity (*very high confidence*).” But it is silent on the larger decline of deaths during extreme cold events.

The observed decline in US heat-related mortality has been specifically attributed to adaptation. Wang et al. (2018) exploited the spatial variability of heatwave-related mortality across 209 U.S. cities from 1962 to 2006. While simple correlation appeared to imply an increase in mortality risk during heatwaves, accounting for adaptation to heatwave intensity caused the effect to fall to near zero and become statistically insignificant. They used the results of their epidemiological model to project heat-related mortality out to 2050 under four RCP warming scenarios (including RCP8.5) with and without adaptive behavior. Assuming people continue to adapt to the heatwave risks in the regions in which they live Wang et al. project not only no increase in heat-related mortality but an overall decrease for the US as a whole. They conclude that

“Ignoring adaptation would result in a substantial overestimate of future mortality related to heat waves... Accounting for adaptation, the overall heat-related mortality by 2050 would not change substantially over time compared to 2006.”

### *10.3.2 Mortality risks and energy costs*

A 2016 study of US long term mortality risks associated with temperature variations (Barreca et al. 2016 ) showed that increases in mortality across the US are associated both with cold weather and hot weather. But over time, the introduction of electricity and the adoption of central heating and air conditioning (AC) dramatically reduced both risks, especially those associated with hot weather. Prior to 1960, a day above 90°F (32°C) added 2.2 percent to the average mortality risk rate, but after 1960 the same weather added only 0.3 percent to mortality risk, an 85 percent reduction. Prior to 1960 temperatures below 39°F (4°C) added about 1 percent to mortality risk but after 1960 the same weather only added about half that amount. Adaptation through conventional household improvements dramatically reduced public vulnerability to weather extremes. The entire reduction in hot weather mortality was attributable to widespread adoption of indoor AC, which depended on the availability of reliable and affordable electricity.

The corollary of this finding is that the use of heating and cooling systems depends on energy being affordable. Doremus et al. (2022) showed that wealthy and poor households in the US adjust their energy expenditures at similar rates in response to moderate temperature swings, but not in response to extreme temperature swings. When temperatures swing to very cold levels ( $< 5^{\circ}\text{C}$ ) energy spending in high-income households rises by 1.2 percent but in low-income households by only 0.5 percent. On very hot days ( $> 30^{\circ}\text{C}$ ) electricity spending in high-income households rises by 0.5 percent but does not change at all in low-income households. The latter result is observed even in subsamples where all households have AC. The implication is that even with widespread adoption of home heating and cooling systems, inability to afford energy leaves low-income households exposed to weather extremes.

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# 11 CLIMATE CHANGE, THE ECONOMY AND THE SOCIAL COST OF CARBON

## Chapter summary

*Economists have long considered climate a relatively unimportant factor in economic growth, a view echoed by the IPCC itself in the AR5. Mainstream climate economics has recognized that CO<sub>2</sub>-induced warming may have some negative economic effects but they are too small to justify aggressive abatement policy, and trying to “stop” or cap global warming even at levels well above the Paris target would be worse than doing nothing. An influential study in 2012 suggested that global warming would harm growth in poor countries but the finding has subsequently been found not to be robust. Studies that take full account of modeling uncertainties either find no evidence of a negative effect on global growth from CO<sub>2</sub> emissions or find poor countries as likely to benefit from it as rich countries.*

*Social Cost of Carbon (SCC) estimates are highly uncertain due to unknowns in future economic growth, socioeconomic pathways, discount rates, climate damages, and system responses. The SCC is not intrinsically informative as to the economic or societal impacts of climate change. It provides an index connecting large networks of assumptions about the climate and the economy to a dollar value. Some assumptions yield a high SCC and others yield a low or negative SCC (i.e. a social benefit of emissions). The evidence for or against the underlying assumptions needs to be established independently; the resulting SCC adds no additional information about the validity of those assumptions. Consideration of potential tipping points at present does not justify major revisions to SCC estimates.*

## 11.1 Climate change and economic growth

### 11.1.1 Overview: climate is a relatively minor issue for a modern economy

It has long been noted that economies tend to do poorly in very cold and very hot regions, with the optimum somewhere in between (Nordhaus 2006). Temperature-sensitive economic activity migrates, whenever possible, to where it is best suited, and society always adapts to the local climate. Based in part on these observations, in 1992 Thomas Schelling, then President of the American Economic Association, argued that any effects of climate change on US economic activity would be small relative to the many other changes that would happen.

... Manufacturing rarely depends on climate, and where temperature and humidity used to make a difference, air conditioning has intervened. When Toyota chooses among Ohio, Alabama, and Southern California for locating an automobile assembly, geographical considerations are important, but not because of climate... Finance is little affected by climate; similarly for health care, or education, or broadcasting. Transportation can be affected, but improvements in all-weather landing and take-off in the last 30 years are greater than any differences that climate makes. If the average effect is a warming, iced waterways and snow removal may decline in importance. Construction is affected, mainly by cold, and if the average effect is in the direction of warming, construction may benefit slightly.

It is really agriculture that is affected. But even if agricultural productivity declined by a third over the next half century, the per capita GNP we might have achieved by 2050 we would achieve only in 2051. ...

I conclude that in the United States, and probably Japan, Western Europe, and other developed countries, the impact on economic output will be negligible and unlikely to be noticed.

(Schelling 1992, emphasis added)

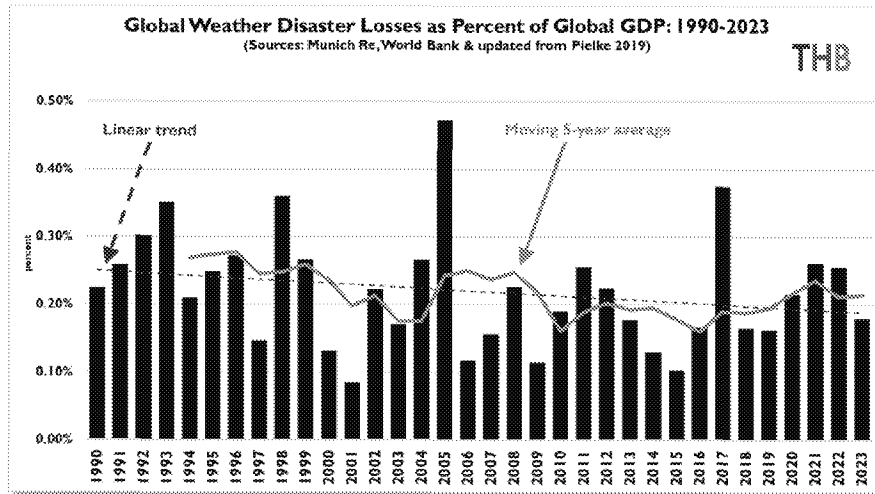
Thirty years later virtually the identical point was made by the IPCC itself in the Fifth Assessment Report:

**For most economic sectors, the impact of climate change will be small relative to the impacts of other drivers.** Changes in population, age, income, technology, relative prices, lifestyle, regulation, governance, and many other aspects of socioeconomic development will have an impact on the supply and demand of economic goods and services that is large relative to the impact of climate change.

(Arent et al. 2014, emphasis added)

That statement is validated by experience. Since 1900, the average global surface temperature anomaly warmed 1.3°C, about as much as the IPCC predicts will occur in the next century under a moderate emissions scenario. But even as the globe warmed and the population quintupled, humanity prospered as never before. For example, global average lifespan went from thirty-two years to seventy-two years, economic activity per capita grew by a factor of seven, and the death rate from extreme weather events plummeted by a factor of fifty!

While extreme weather events are costly, in all modern economies they are becoming steadily less and less important (Formetta and Feyen 2019). Since 1990 weather-related disaster losses have declined as a proportion of global GDP (Pielke Jr 2018, 2020) as have mortality risks (Formetta and Feyen 2019). While economic weather-related insurance payouts are rising, this is fully explained by the growth in the size of the economy and the value of the insured asset stock. Past increases in episodes extreme weather have not had a significant effect (positive or negative) on the market value of insurance firms (Hu and McKittrick 2015). Nor have past extreme weather events had a significant effect on US banks' performance (Blickle et al. 2021). The following chart is illustrative:



**Figure 11.1** Global weather losses as a fraction of GDP. Source: Pielke Jr. (2023)

For these reasons, economists have long been reluctant to endorse attempts to “stop” climate change or even aggressively reduce GHG emissions because the costs would not be worth it. As one critic of the economics of climate policy put it:

Mainstream climate economics takes global warming seriously, but perplexingly concludes that the optimal economic policy is to almost do nothing about it... The contrast is striking. While climate science is sending out loud-and-clear messages that fossil-fuel disinvestment must start now, letting go of coal and oil and diverting resources into renewable energy technology systems, to keep warming below the 2°C limit (IPCC 2014), mainstream climate economics claims that overly ambitious climate targets will unnecessarily hurt the economy and immediate de-carbonization is too expensive. Most climate economists thus recommend humanity to just wait-and-see.

(Storm 2017)

The mainstream economics position on the climate policy question is best represented by the findings over the past three decades from Integrated Assessment Models (IAMs) of climate change policy, for which Yale economist William Nordhaus was awarded the 2018 Nobel Memorial Prize in economics. IAMs combine economic, climate, and social data into a unified framework for simulating climate damages and evaluating the optimal policy response (Resources for the Future 2025). Nordhaus’ work has generally supported modest global climate policy, with aggressive measures largely deferred to later in the century. Nordhaus developed the so-called Dynamic Integrated Model of the Climate and Economy model, or DICE, in the early 1990s (Nordhaus 1993) to study the interaction between climate change, climate policy, and global economic growth over long times. DICE assumes global emission control can be coordinated at no cost and asks what the optimal policy target should be. The climate component of the DICE model is based on simplified climatological modeling. The version of DICE at the time of Nordhaus’ Nobel Prize award was described in Nordhaus (2018); it had a climate sensitivity parameter of 3.1°C for CO<sub>2</sub> doubling, consistent with the best estimate in contemporary IPCC reports (3.0°C).

The baseline (no policy) scenario incurs only \$0.4T in global abatement costs and leads to \$134.2T (trillion dollars) in global climate damages for a total cost of \$134.6T. The climate model component of DICE projects 4.1°C warming by 2100 relative to preindustrial temperatures. Note that this is a higher estimate of warming than many IPCC climate models.

The Optimal Policy scenario barely deviates from the business-as-usual path. It aims for +3.5°C warming, in other words we modestly scale back fossil fuel use and otherwise just live with almost all the warming. This suggests that most CO<sub>2</sub> emissions are less harmful than the policies that would be necessary to abate them. Trying to prevent warming causes costs quickly to outstrip the benefits. Pursuing a goal of capping warming at 2.5°C creates total costs of \$177.8T, which is \$43.2T worse than doing nothing at all. Nordhaus didn't evaluate trying to reach a Paris-type target of 1.5°C warming but it would be even worse.

A subsequent edition of DICE includes higher assumed damages from warming which, not surprisingly leads to more aggressive policy recommendations, as explained in the section below on the Social Cost of Carbon.

### *11.1.2 Empirical analysis of climate change and economic growth*

Many other studies have used econometric methods applied to historical data, instead of IAMs, to study the potential impact of climate change on economic growth. Dell et al. (2012, herein DJO12) was an influential study that used a multi-country panel of national-level data spanning 1950 to 2005, in which they matched climate and economic data by averaging temperature from the local grid cell level up to the national level using population weights. They found that warming yields an insignificant positive effect on income growth in rich countries but a significant negative effect in poor countries. Moore and Diaz (2015) modified the DICE model to take that finding into account and concluded that it implied a dramatically higher Social Cost of Carbon due to the compounding effects of income loss over time.

A large subsequent literature has debated the robustness of the DJO12 findings. Burke et al. (2015) analyzed a global panel with temperatures averaged up to the national level and found a negative effect on growth from warming in rich and poor countries alike when the national average temperature is above 13°C. Zhao et al. (2018) used the G-Econ data set of Nordhaus (2006), which breaks economic activity down to the grid cell level, replicated DJO12-type results on the same subset of countries as used in DJO12 but then showed that on the full global sample warming increases growth in rich countries and poor countries alike, though the positive effect in the latter group is confined to where local temperatures are below about 16°C. Greßer et al. (2021) developed a regional economic data set for 1,542 sub-national regions around the world between 2005 and 2015 and found temperature had no effect on growth. Yang et al. (2023) updated the DJO12 data set and applied an estimator robust to mixed sample frequencies, finding that while temperature shocks exerted a temporary effect on income levels, they did not have a significant lasting effect on growth rates.

Newell et al. (2021) noted that there is no underlying theory to guide econometric model specification in this literature. Taking into account the arbitrary choices of which explanatory variables to include they identified over 800 possible model specifications. Using the Burke et al. (2015) data they used an estimation method that accounts for model uncertainty and found that the model form preferred by Burke et al. (2015), which implied negative effects of warming on growth even in rich countries, is explicitly excluded by the optimal model selection algorithm. Overall they could not detect a temperature effect on GDP or GDP growth, and they estimated the 95% confidence interval for the impact on global growth as of 2100 even under the exaggerated RCP8.5 warming scenario spans –86 percent to +388 percent. In other words the net effect is likely positive but too uncertain to distinguish from zero.

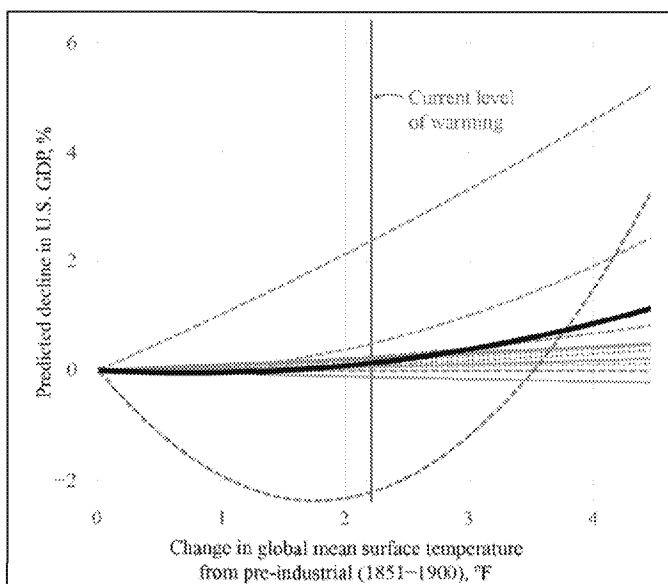


Barker (2023) criticized the DJO12 assumption that countries can be grouped into fixed “poor” and “rich” categories based on their incomes many decades ago. He noted that many countries were once poor but became rich over time, and if this is taken into account the original temperature effects reported by Dell et al. became small and insignificant.

Berg et al. (2023) argued that countries shouldn’t be grouped into large Rich/Poor categories because they are too heterogeneous. They instead estimated country-specific temperature response coefficients then grouped countries with similar response coefficients into small panels. They separately estimated responses to global and idiosyncratic local temperature shocks to better identify the climate signal in weather data. Overall they found countries experiencing negative effects of warming on growth outnumbered those experiencing positive effects, but only temporarily: eventually the effects reverse such that about twice as many countries experience a net positive growth effect. They also found global (as opposed to local) temperature changes are much more likely to benefit growth in poor countries than rich ones. In a simulation to 2100 even using the extreme RCP8.5 scenario they computed the average global GDP loss would be only 1.9% compared to a scenario with no warming. That is, instead of the economy growing 400% it would grow 398%. The implication of Nordhaus’ earlier analysis is that trying to prevent the warming would lead to far less than 398% growth.

To summarize, economists have long considered climate a relatively unimportant factor in economic growth, a view echoed by the IPCC itself in the Fifth Assessment Report. Mainstream climate economics has recognized that CO<sub>2</sub>-induced warming may have some negative economic effects but they are too small to justify aggressive abatement policy, and trying to “stop” or cap global warming even at levels well above the Paris target would be worse than doing nothing. An influential study in 2012 suggested that global warming would harm growth in poor countries but the finding has subsequently been found not to be robust. Studies that take full account of modeling uncertainties either find no evidence of a negative effect on global growth from CO<sub>2</sub> emissions or find poor countries as likely to benefit from it as rich countries.

The expectation that significant global warming would have a small impact on the U.S. economy was acknowledged quietly by the Biden Administration, even as the President was proclaiming a climate emergency. Figure 11.2, from a 2023 OMB-CEA [ [HYPERLINK "https://www.whitehouse.gov/cea/written-materials/2023/03/14/methodologies-and-considerations-for-integrating-the-physical-and-transition-risks-of-climate-change-into-macroeconomic-forecasting-for-the-presidents-budget/"](https://www.whitehouse.gov/cea/written-materials/2023/03/14/methodologies-and-considerations-for-integrating-the-physical-and-transition-risks-of-climate-change-into-macroeconomic-forecasting-for-the-presidents-budget/) ], **[note link dead, updated one to come]** shows the expected decrement in U.S. GDP as a function of temperature rise. The colored lines show the results of a dozen peer-reviewed published studies while the solid black line is their average. The figure could be summarized as “a few percent impact for a few degrees of warming”. Given that the economy’s annual growth rate is expected to be 1-2 percent, the impact of a warming globe is indeed negligible.



**Figure 11.2:** Decline in US GDP per degree of warming. Source: XX

## 11.2 Models of the Social Cost of Carbon

The Social Cost of Carbon (SCC) is a tool for quantifying the economic impact of carbon dioxide emissions, helping policymakers weigh the costs and benefits of climate policies. It estimates the damage caused by emitting one additional ton of CO<sub>2</sub>, expressed in dollars. More formally, the SCC is the discounted present value of the current and future marginal loss of economic welfare due to an additional ton of CO<sub>2</sub> entering the atmosphere.

### 11.2.1 Estimating the SCC

Although the literature refers to “estimates” of the SCC, it is not estimated in the way other economic statistics are estimated. For instance, data on market transactions including prices and quantities can be used to estimate the current inflation rate or the growth rate of per capita real Gross Domestic Product, and there are well-understood uncertainties associated with these quantities. But there are no market data available to measure many if not most of the marginal damages or benefits believed to be associated with CO<sub>2</sub> emissions, so these need to be imputed using economic models.

For example, an influential component of some SCC calculations is the perceived social cost associated with changed risk of future mortality due to extreme weather. There is no market in which people can directly attach a price to that risk. At best economists can try to infer such values by looking at transactions in related markets such as real estate or insurance, but isolating the component of price changes attributable to atmospheric CO<sub>2</sub> levels is very difficult.

Economists use IAMs to compute the SCC. Two of the best known are the Climate Framework for Uncertainty, Negotiation and Distribution (“FUND”, Tol 1997) and Nordaus’ DICE. IAMs embed a “damage function” or set of functions relating ambient temperature to local economic conditions. The assumptions embedded in the damage function will largely determine the resulting SCC. IAMs also assume a long-term discount rate or, as in DICE, compute the optimal internal discount rate as part of the solution.

One approach to developing a damage function is to begin with estimates of the costs (or benefits) of warming in specific sectors in countries around the world and aggregate up to a global amount. This was the approach used in FUND. An alternative approach is to develop a simple equation that penalizes global income according to a simple quadratic function of the average global temperature. This approach was used in DICE. In the case of the FUND model many hundreds of parameters had to be selected, whereas in DICE only three were needed and were originally chosen to assign a predetermined penalty (1.2%) to global output as of 3°C warming, with a quadratic term implying that damages grow with the square of the global average temperature anomaly. Barrage and Nordhaus (2024) recently changed the parameters to increase the penalty at 3°C to 1.6%, and added a discrete additional 1.0% GDP penalty at 3°C warming to account for “tipping points” (discrete large-scale environmental changes triggered by crossing a warming threshold) and a “judgmental adjustment” of 0.5% for excluded impacts at 3°C warming. Not surprisingly the newer version of DICE generates much higher SCC estimates than before.

The concepts of estimation and uncertainty do not readily apply to SCC calculations. By comparison, the question of whether precipitation has trended up or down along the South Carolina coast for the past hundred years can be addressed by collecting rainfall data, estimating a trend parameter and calculating statistical confidence intervals using methods with well-understood mathematical properties. In this way uncertainty can, in principle, be resolved by collecting more data and applying more accurate methods. But no amount of data collection can change the fact that many components of the SCC are unknown and rely on judgment and opinion based on knowledge of the underlying literature on the physical effects of climate change.

SCC calculations are thus best thought of as “if-then” statements: *if* the following assumptions hold, *then* the SCC is \$X per tonne. The list of ‘if’ statements includes the premise that the world’s climate and economy work according to the representation in the IAM. One way this may fail to hold is in the timing of warming. Every IAM assumes a value of the Equilibrium Climate Sensitivity (ECS), which controls the amount of warming that results from CO<sub>2</sub> emissions and can be freely varied for the purpose of generating a distribution of SCC values associated with uncertainties over ECS. But as Roe and Baumann (2013) pointed out, time-to-equilibrium increases with the square of ECS, so an upward adjustment of the ECS parameter without an appropriate slowing down of the adjustment process can yield distorted present value damage estimates. In particular, the upper tail of warming associated with some commonly-used ECS distributions is physically impossible for even a thousand years into the future (Roe and Baumann 2013) yet in an IAM would be realized within a couple of centuries. Failure to align ECS with time-to-equilibrium will lead to an overestimate of the SCC value.

### 11.2.2 Variations in the SCC

Every level of the IAM calculation includes assumptions, some more influential than others. Key assumptions include the following.

- The discount rate: Climate damages accrue over a long time horizon, and costs a century or two in the future need to be discounted to the present. The higher the discount rate the smaller the present value of future damages and vice versa. The discount rate represents the opportunity cost of spending money today rather than investing it and then having more to spend tomorrow. Some economists have argued for the use of very low discount rates in SCC calculations, resulting in policy recommendations that favor relatively large immediate investments in CO<sub>2</sub> emission reductions. The downside is that other investments could potentially earn a larger rate of return for society.

- **Equilibrium Climate Sensitivity:** IAMs have customarily employed a value of 3.0°C or 3.1°C following the IPCC’s guidance. Empirically-estimated ECS values tend to be lower than this (see Chapter 9). Dayaratna et al. (2017, 2020, 2023) have shown that use of lower empirically-derived ECS values dramatically lower the resulting SCC estimate, even when low discount rates are used.
- **Damage function coefficients:** IAMs assume CO<sub>2</sub> and warming cause net harms that increase exponentially with temperature. More recently, IAMs have also incorporated effects from assumed potential climate tipping points. The FUND model took limited but explicit account of CO<sub>2</sub> fertilization effects in agriculture. Since the coefficients were selected prior the publication of the current evidence of global greening and the magnitude of benefits to crops from elevated CO<sub>2</sub> (see Chapters 2 and 10) the growth effects are likely understated. The DICE model (and others) did not explicitly include any CO<sub>2</sub> fertilization benefit, except to the extent it was taken into account in the literature consulted when picking the damage function coefficients. The damage function in FUND contains a region in which low warming yields net benefits in many regions, a finding which is supported by econometric models of warming and growth (Berg et al. 2023) and econometric simulations of agricultural changes (McKittrick 2025). The DICE damage function, by construction, rules out net benefits at any warming level.
- **Emission scenarios:** IAMs generate SCC estimates that increase as the pre-existing concentration of CO<sub>2</sub> increases. Consequently the value of damages later in the century will be higher, depending on the assumed baseline emissions over the coming decades.
- **Abatement costs:** IAMs represent the cost to the economy of reducing CO<sub>2</sub> emissions. If CO<sub>2</sub> emission reductions are assumed to be inexpensive, then the model will conclude that the optimal policy should aim for deeper emission cuts and vice versa.

It is informative to ascertain whether SCC results are invariant to changes in some assumptions. But when different assumptions result in higher or lower SCC values, the change in the SCC value does not provide *prima facie* evidence about the validity of the assumptions. For example, in 2023 the US Environmental Protection Agency raised its preferred SCC value about 5-fold over the estimates it had issued ten years earlier. This is not because new data had been collected or better mathematical methods had been invented, but because new assumptions had been used, and the validity of those assumptions was a separate question. One was that global agricultural damages were far higher than previously assumed, based on an analysis in Moore et al. (2017). But as discussed in Chapter 10, McKittrick (2025) showed that Moore et al. (2017) had used a database in which half the CO<sub>2</sub> change observations were missing. When as many of those observations as possible were recovered from underlying sources and the analysis was rerun, the projected crop yield losses disappeared and turned into gains at all warming levels. Hence the portion of the EPA’s SCC revision attributable to agricultural yield losses was unwarranted.

### 11.2.3 Evidence for low SCC

Chapter 2 reviewed evidence on climate change and greening, and Chapter 10 looked at climate change and US agriculture. Evidence shows that CO<sub>2</sub> fertilization has a stronger beneficial effect on agriculture than was known at the time that IAMs like DICE and FUND were parameterized. In particular Haverd et

al. (2020) found the observed CO<sub>2</sub> fertilization rate has been almost double what had been predicted by crop models. Dayaratna et al. (2023) used the updated empirical ECS distribution estimate of Lewis (2022), which assimilates modern instrumental and paleoclimatic temperature records, and allowed for a 30 percent gain in the CO<sub>2</sub> fertilization benefit in the FUND model, and found that, even at a low discount rate of 2.5 percent, the median SCC as of 2050 is only \$18.67, with a 24 percent probability of the true value being negative. At a five percent discount rate the median SCC value is negative until the mid-2040s and at 2050 was only \$0.37 with a 49 percent probability of being negative. Thus, under reasonable assumptions a mainstream IAM using updated scientific inputs yields evidence consistent with the SCC not being significantly greater than zero.

It should also be noted that the SCC is focused on the social costs of CO<sub>2</sub> emissions from fossil fuel use. It does not measure the private marginal benefits to consumers and society from the availability of fossil fuels. Public willingness to pay for fuels of all types indicates the value to society of reliable, abundant fossil energy. Tol (2017) estimates that the private benefit of carbon is large relative to the social cost. This can be illustrated by noting that the price of a gallon of gas indicates the marginal value to the consumer of the fuel. Suppose we assume a relatively high Social Cost of Carbon of, say, \$75 per tonne. Deflated by a MCPF value of 1.5 that would result in a carbon tax of \$50 per tonne, which equates to about 44 cents per gallon of gas (Lavelle 2019). A pre-tax price of \$3.00 per gallon would imply the marginal social benefit of the fuel is nearly seven times the marginal social cost.

#### 11.2.4 Tipping points

SCC calculations typically consider gradual impacts of a warming climate, such as slowly-melting glaciers and increasing average temperature. A driver of potentially high values of the Social Cost of Carbon (SCC) is the introduction into models of discrete catastrophic outcomes associated with abrupt changes (Dietz et al. 2021). They are often referred to as “tipping points.”

The term “tipping point” mingles two different physical concepts that pose different research challenges. Many physical systems are inherently stable unless acted upon with sufficient external energy. For example an ice cap might remain intact over a wide range of temperatures but once the temperature crosses the 0°C threshold it melts. Such discontinuities are ubiquitous in nature and require an external force. Whether the force needs to be large relative to the size of the system depends on the underlying stability of the system.

A different type of tipping point is called a *bifurcation* and arises from the study of the internal dynamics of nonlinear systems (Crawford 1991). Many systems have been observed to have more than one equilibrium point and can move between them with minimal or no external influence. For example a weather system might have two different equilibrium states: one calm and one with a tornado. A transition from one to another can happen either with no external force or with a minuscule change, such as a flap of the proverbial butterfly’s wings (Shen et al. 2014). The term “tipping point” is sometimes used to mean a bifurcation of this type and implies instability inherent in the system itself, which is not necessarily dependent on outside forces. It depends, instead, on parameters of the system taking values that support the emergence of bifurcations (Crawford 1991).

The two different concepts imply different research questions. Regarding the first we are interested in whether components of the climate system are susceptible to abrupt discontinuities in response to sufficiently-large anthropogenic forcing. Regarding the second we are interested in whether the Earth’s climate system has inherent bifurcations that imply the possibility of abrupt transitions with or without external forcing.

Models have been developed that imply the latter is a possibility. Kypke et al. (2020) presented a simple climate model in which the GHG concentration is one of the parameters that controls the emergence of

bifurcations of the Arctic climate to one with both cold and warm equilibria. If sufficiently high GHG forcing combined with a sufficiently high rate of ocean heat transport are imposed a bifurcation becomes possible. More generally GCMs have been observed to contain bifurcations and multiple equilibria (Brunetti and Ragon 2023).

The possible existence of bifurcations in the Earth's climate system implies abrupt transitions are possible, not just in response to large forcing but to small perturbations as well. This places tipping points into the category of low-likelihood and potentially catastrophic events, such as large meteor strikes. A key question to ask is whether those kinds of tipping points can be predicted. Current research has not resolved that question (Dakos et al 2024) and indeed may not be able to since one implication of the "butterfly effect" is the existence of predictability boundaries of nonlinear systems (Palmer et al. 2014). It is therefore not obvious how to incorporate such possibilities into SCC calculations. Small variations in assumptions will lead to arbitrarily large variations in the resulting SCC with no grounds for choosing among them. If such tipping points are possible the most appropriate stance for economic policy is to maximize resilience to any form of external catastrophe since it is unlikely we could predict or prevent it from happening.

The IPCC AR6 (Chapter 1) focuses mainly on the first type of tipping point, namely an abrupt change in response to external forcing. This is also the meaning associated with popular usage of the "tipping point" concept in discussions of climate change (see [ [HYPERLINK "https://report-2023.global-tipping-points.org/what-is-a-tipping-point/"](https://report-2023.global-tipping-points.org/what-is-a-tipping-point/) ] for example). As summarized by the IPCC AR6, there is evidence of abrupt change in the paleoclimate record, and some of these events have been interpreted as tipping points. Some projections with Earth System Models for example have produced tipping points such as Amazon forest dieback in response to specified values of CO<sub>2</sub> concentration or temperature increases.

The alarm surrounding climate tipping points is reflected by *The Global Tipping Points Report* that was launched at the COP28 on 6 December 2023 (Lenton et al., 2023). It identifies more than 25 parts of the climate system said to constitute tipping points. What gets classified as a climate "tipping point" is a moving target. The most common examples in the literature and assessment reports include: Greenland ice sheet disintegration, West Antarctic ice sheet disintegration, summertime disappearance of Arctic sea ice, Amazon rainforest dieback, coral reef dieoff, thawing of permafrost and methane hydrates, Atlantic Meridional Overturning Circulation collapse, boreal forest shift, West African monsoon shift, and Indian Monsoon shift.

All such tipping points require a certain amount of system instability in order to exhibit an abrupt transition in response to warming. For this reason there seems to be very little to discriminate between a tipping event and natural climate variability. Natural climate variability has in the past produced shifts in the West African and Indian monsoons, Amazon forest and coral reef dieback, and disintegration of the Greenland and West Antarctic ice sheets. These impacts can be reversed on the decadal timescales associated with natural climate variability and ecosystem responses.

Some abrupt changes are potentially more consequential, including collapse of the West Antarctic ice sheet and collapse of the Atlantic Meridional Overturning Circulation (AMOC). The IPCC AR6 WG1 Summary for Policy Makers states:

"The Atlantic Meridional Overturning Circulation is very likely to weaken over the 21st century for all emission scenarios. While there is high confidence in the 21st century decline, there is only low confidence in the magnitude of the trend. There is medium confidence that there will not be an abrupt collapse before 2100." (C.3.4)

"There is limited evidence for low-likelihood, high-impact outcomes (resulting from ice-sheet instability processes characterized by deep uncertainty and in some cases involving tipping

points) that would strongly increase ice loss from the Antarctic Ice Sheet for centuries under high GHG emissions scenarios (e.g., SSP5-8.5)." (B.5.2)

For the purpose of SCC calculations the research question implied by this type of tipping point is whether such events have been observed in the past in climate conditions similar to what we currently experience or will in the near future. The IPCC AR6 finds little evidence for impending collapse of the Atlantic Meridional Overturning Circulation or the West Antarctic ice sheet. It finds there is no tipping point associated with Arctic Sea ice (AR6 Technical Summary p. 76)

Dietz et al. incorporated several potential tipping points (abrupt changes) into an SCC model and found they added about 25 percent to the estimate, mainly associated with thawing permafrost and release of methane hydrates. However the IPCC considers this scenario *very unlikely* (AR6 Technical Summary p. 107).

In summary, there may be unknown bifurcation tipping points that are associated with natural climate processes, but this possibility does not translate into specific guidance on the SCC. There are potential abrupt change points in the climate system in response to warming, although the IPCC assigns low probabilities to most, including the largest ones. When these have been taken into account the result is only a modest increase in the SCC value in the 21<sup>st</sup> century.

#### 11.2.5 Are there alternatives?

It is increasingly being argued that the SCC is too variable to be useful for policymakers. Cambridge Econometrics (Thoung 2017) stated it's "time to kill it" due to uncertainties. The UK and EU no longer use SCC for policy appraisal, opting for "target-consistent" carbon pricing (UK Department for Energy Security and Net Zero 2022, Dunne 2017). However the uncertainty of SCC estimates doesn't mean that other regulatory measures are inherently better or more efficient. Many emissions regulations (such as electric vehicle mandates, renewable energy mandates, energy efficiency regulations and bans on certain types of home appliances) cost far more per tonne of abatement than any mainstream SCC estimate which is sufficient for establishing they fail a cost-benefit test.

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## 12 GLOBAL CLIMATE IMPACTS OF U.S. EMISSIONS POLICIES

### Chapter Summary

*U.S. policy actions are expected to have undetectably small direct impacts on the global climate and any effects will emerge only with long delays.*

### 12.1 The scale problem

The emissions rates and atmospheric concentrations of criteria air contaminants are closely connected because their lifetimes are short and their concentrations are small; when local emissions are reduced the local pollution concentration drops rapidly, usually within a few days. But the global average CO<sub>2</sub> concentration behaves very differently, since emissions mix globally and the global carbon cycle is vast and slow. Any change in local CO<sub>2</sub> emissions today will have only a very small global effect, and only with a long delay.

Following the emission of a pulse (release) of CO<sub>2</sub> into the atmosphere only about  $40 \pm 15$  percent of the emitted CO<sub>2</sub> will have been sequestered after twenty years. That fraction rises to  $75 \pm 10$  percent after a thousand years, and the remainder will be gradually removed over the ensuing tens of thousands of years (Ciais et al. 2013, pp. 472-473). Consequently, any reduction in U.S. emissions would only modestly slow, but not prevent, the rise of global CO<sub>2</sub> concentration. And even if global emissions were to stop tomorrow, it take decades or centuries to see a meaningful reduction in the global CO<sub>2</sub> concentration and hence human influences on the climate.

Reducing the atmospheric stock of CO<sub>2</sub> would require emissions to fall below the natural sequestration rate, assuming the entire increase is anthropogenic. Since that rate has been averaging about 50% of emissions in recent decades, a reduction of global emissions by 50% would (at least temporarily) halt the rise in atmospheric CO<sub>2</sub>. The 1997 Kyoto Protocol proposed to cap industrial nations' CO<sub>2</sub> emissions at a modest five percent below 1990 levels by the year 2012. Even though this policy was too difficult for most nations to implement, full compliance would not have substantially reduced atmospheric CO<sub>2</sub> levels. It would only have slightly slowed CO<sub>2</sub> growth, reaching the projected year 2100 level in 2105 instead (Wigley 1998). Lomborg (2016) estimated that full compliance with the Paris Accord would not stop warming, it would only prevent about 0.1C warming and delay hitting the baseline year 2100 temperature levels by about a decade.

Thus, in contrast with conventional air pollution control, even drastic local actions will have negligible local effects, and only with a long delay. The practice of referring to unilateral US reductions as “combatting climate change” or “taking action on climate” therefore reflects a profound misunderstanding of the scale of the issue.

### 12.2 Case study: US motor vehicle emissions

The scale problem can be illustrated with reference to U.S. motor vehicles. The EPA's 2009 Endangerment Finding focused on CO<sub>2</sub> emissions from cars and light-duty trucks in the U.S. because

Section 202(a) of Clean Air Act mandates the EPA to set emissions standards for motor vehicles if pollutants are found to endanger public health or welfare. The 2009 Endangerment Finding therefore obligated the EPA to regulate emissions from new motor vehicles, ostensibly to reduce or eliminate climate-related harms to the US public.

Two questions that naturally arise are: (1) How large a reduction in CO<sub>2</sub> emissions would result from such regulation? and (2) What would be the climate impact of such regulation?

The first question can be addressed by comparing US vehicle-based CO<sub>2</sub> emissions to the global total. The second question can be addressed by using the fact that the reduction in global warming would be, according to the models relied upon by the EPA, proportional to the reduction in global emissions, keeping in mind that the change in the CO<sub>2</sub> content of the atmosphere in any given year is the result of total global CO<sub>2</sub> emissions, not just U.S. emissions.

In 2022, the emissions from U.S. cars and light duty trucks totaled 1.05 billion metric tons of carbon dioxide (GtCO<sub>2</sub>, EPA 2024). Meanwhile global CO<sub>2</sub> emissions from energy use totaled 34.6 GtCO<sub>2</sub> (Energy Institute 2024). Hence U.S. cars and light trucks account for only 3.0% of global energy-related CO<sub>2</sub> emissions. To a first approximation we can say that even eliminating all US vehicle-based emissions would change the multidecadal warming trend by at most 3%. For the period 1979-2023, which has the most extensive global coverage of a variety of weather data types, warming trends are determined to a precision of about  $\pm 15\%$ , so the impact of reducing the rate of global warming by eliminating U.S. vehicle CO<sub>2</sub> emissions would be far below the limits of measurability.

Given that global-average temperature is the most direct climate change metric, impacts on any secondary climate metrics (e.g. severe weather, floods, drought, etc.) from reducing U.S. vehicle CO<sub>2</sub> emissions would be even less measurable.

Consequently, in contrast to the case of local air contaminants like particulates and ozone, even the most aggressive regulatory actions on GHG emissions from U.S. vehicles cannot be expected to remediate alleged climate dangers to the US public on any even remotely-measurable scale.

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EPA (2024) *Fast Facts: U.S. Transportation Sector Greenhouse Gas Emissions 1990-2022*. Available online at [ [HYPERLINK "https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockkey=P101AKR0.pdf"](https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockkey=P101AKR0.pdf) ]

Energy Institute (2024) *Statistical Review of World Energy*. Available online at [ [HYPERLINK "https://www.energyinst.org/statistical-review"](https://www.energyinst.org/statistical-review) ]

## 13 GLOSSARY

**2XCO<sub>2</sub>**: Doubling of the atmospheric carbon dioxide (CO<sub>2</sub>), a commonly used baseline for addressing climate change. In 2025, atmospheric CO<sub>2</sub> concentrations were approximately 50% of the way to 2XCO<sub>2</sub> compared to 1800.

**ABATEMENT**: In the context of environmental policy, the reduction of emissions.

**ACE (Accumulated Cyclone Energy)**: A statistical measure of a tropical cyclone's energy accumulated over its lifetime, calculated from a summation of the square of maximum sustained wind speeds.

**ACIDIFICATION**: A commonly used term for the reduction in ocean pH from more alkaline to less alkaline values.

**ACRIM (Active Cavity Radiometer Irradiance Monitor) GAP**: the gap in total solar irradiance data between 1989 and 1991 caused by a delay in the launch of a satellite-borne monitor in time to overlap and intercalibrate with the prior system.

**AEROSOLS**: Tiny solid or liquid particles suspended in the air.

**ALKALINE**: Having a chemical pH greater than 7.0. The “opposite” of acidic, which means a pH less than 7.0.

**AMBIENT**: Relating to the immediate surroundings of something.

**ANTHROPOGENIC**: Created by humans.

**AR (Assessment Reports)**: Periodic assessments published by the Intergovernmental Panel on Climate Change evaluating current knowledge of the climate system, global change, and associated issues. An AR now consists of reports from three working groups, the first (WG1) concerned with physical science and the others concerned with societal impacts and mitigation strategies. The most recent was the AR6.

**ATTRIBUTION**: Assertion of a causal relation, chiefly from anthropogenic GHG emissions to observed climate patterns.

**AUTOCORRELATION**: The phenomenon in which the current value of a random time series variable is correlated with its value in a previous time period.

**BIOMASS**: The total quantity or weight of organic matter in a given area or volume.

**CARBON**: The 6<sup>th</sup> element in the periodic table. Popularly used as a shorthand term for carbon dioxide.

**CMIP (Coupled Model Intercomparison Project)**: The Intergovernmental Panel on Climate Change's organized effort to compare many different global ocean-atmosphere climate models when they are all forced with the same emissions scenario(s). The two most recent were the CMIP5 and CMIP6 for, respectively, AR5 and AR6.

**CONUS**: The contiguous 48 U.S. states.

**DICE (Dynamic Integrated model of the Climate and Economy)**: An Integrated Assessment Model developed by William Nordhaus in 1993.

**DISCOUNT RATE**: The interest rate used to convert future costs and benefits into their present value. Varies inversely with present value so a high discount rate reduces the present value of future costs and benefits.

**DRY ICE**: Frozen carbon dioxide.

**ECONOMETRICS:** The branch of economics concerned with the use of statistical methods (chiefly multiple regression) to analyse economic systems.

**ECS (Equilibrium Climate Sensitivity):** The total amount of eventual global-average surface warming in response to a hypothetical doubling of the atmospheric CO<sub>2</sub> concentration compared to pre-Industrial levels.

**EL NIÑO:** The warm phase of the El Niño – Southern Oscillation, involving weaker upwelling of cold water off the South American coast and weaker Pacific trade winds.

**EMISSIONS SCENARIO:** An assumed scenario of future greenhouse gas emissions (or resulting atmospheric concentrations) based upon assumptions regarding global economic activity, the prevalence of fossil fuel use, and (sometimes) global carbon cycle model estimates of the rate of CO<sub>2</sub> uptake by land and ocean.

**ENDANGERMENT FINDING (EF):** The 2009 finding by the Administrator of the Environmental Protection Agency that emissions of well-mixed greenhouse gases (primarily CO<sub>2</sub>) endanger human health and welfare.

**ENSO:** El Niño – Southern Oscillation, a prominent natural climate fluctuation involving year-to-year variations in the upwelling of cold water off the equatorial coast of South America and associated strengthening or weakening of trade winds across the Pacific Ocean.

**FACE: (Free-Air CO<sub>2</sub> Enrichment)** Large-scale open-air studies that expose plants to elevated CO<sub>2</sub> levels, simulating future climate scenarios.

**FOSSIL FUEL:** A natural hydrocarbon fuel such as coal, oil, or natural gas formed in the geological past from the remains of living organisms.

**FUND (Framework for Uncertainty, Negotiation, and Distribution):** An Integrated Assessment Model developed by Richard Tol in 1997.

**GBR (Great Barrier Reef):** The world's largest coral reef ecosystem located off the northeast coast of Australia.

**GDP (Gross Domestic Product):** Total market value of all the final goods and services produced within a country's border, usually over one year.

**GHCN (Global Historical Climatology Network):** A time-varying number of globally distributed weather stations making hourly, daily, or monthly measurements of precipitation, temperature and sometimes snowfall and snow depth.

**GLOBAL GREENING:** The satellite-observed increase in greenness in most vegetated land areas observed since the early 1980s.

**GNP (Gross National Product):** Total market value of all the final goods and services produced by the citizens of a country, including exports and imports, usually over one year.

**GDP (Gross National Product):** Total market value of all the domestically-produced final goods and services produced by the citizens of a country, usually over one year.

**GREENHOUSE EFFECT (GHE):** The tendency for any planetary atmosphere containing greenhouse gases to be warmer in the lowest layers than if those gases did not exist.

**GREENHOUSE GAS (GHG):** An atmospheric gas that absorbs and emits infrared radiation, especially water vapor, CO<sub>2</sub>, and methane.

**HURST PHENOMENON:** See long term persistence.

**HYDROLOGY:** The study of the movement of water, especially on land and in the atmosphere.

**IAM (Integrated Assessment Model):** A computerized tool that combines economics, climate science, and social sciences to provide quantitative relationships between human and Earth systems, helping to inform policy decisions.

**IEA (International Energy Agency):** A Paris-based intergovernmental organization, established in 1974, that provides policy recommendations, analysis and data on the global energy sector.

**IPCC (Intergovernmental Panel on Climate Change):** A panel of international experts and governmental representatives established by the United Nations and World Meteorological Organization in 1988 to provide governments at all levels with scientific information that they can use to develop climate policies.

**IR (Infrared):** Heat radiation that all solid objects and greenhouse gases emit by virtue of their temperature.

**LA NIÑA:** The cool phase of ENSO, involving stronger upwelling of cold water off the South American coast and stronger Pacific trade winds.

**LONG TERM PERSISTENCE (LTP, or HURST PHENOMENON):** A form of autocorrelation in which random fluctuations induce long term but not permanent changes in the mean value of a series, which shows up in some climate data series as cyclical or trending patterns on short time scales.

**MAIZE:** Corn.

**MODEL:** A computer code or collection of codes which quantify our knowledge of various processes and the interactions between those processes.

**MORTALITY:** Death or number of deaths, usually expressed for a specific population and period.

**NCA (National Climate Assessment):** A periodic report mandated by the Global Change Research Act of 1990 summarizing the impact of climate change on the United States. There have been five NCA reports: NCA1 (2000), NCA2 (2009), NCA3 (2014), NCA4 (2017-18), and NCA5 (2023).

**OECD (Organization for Economic Cooperation and Development):** A group of 38 member countries that have a democratic system of government and free economic systems.

**PALEOCLIMATE:** Climate of the distant past, before modern weather instruments were widely used (typically pre-1850), necessitating the use of “proxy” measurements such as tree rings, ice core, pollen records, etc.

**PDI (Power Dissipation Index):** A statistical estimate of the accumulated destructive potential of a tropical cyclone over time, calculated as a summation of the cube of the maximum sustained wind speeds.

**PHOTOSYNTHESIS:** The process by which plants grow, requiring carbon dioxide, water, and light at sufficiently warm temperatures (10 to 35 deg. C for optimal function).

**PPM:** Parts per million, a measure of the concentration of a substance in (for example) the atmosphere

**PRE-INDUSTRIAL:** The near-term historical period before which human greenhouse gas emissions were considered significant, usually assumed to be the mid-1700s.

**RADIATIVE FEEDBACK:** A change in the balance between absorbed solar radiation and emitted infrared (IR) radiation, referenced to the top of the atmosphere, caused by changes in surface temperature.

**RADIATIVE FORCING:** The change in the balance between absorbed solar radiation and emitted infrared (IR) radiation, referenced to the top of the atmosphere, caused by changes in greenhouse gases, anthropogenic aerosols, volcanoes, etc.

**RCP (Representative Concentration Pathway) SCENARIOS:** Different scenarios for future greenhouse gas emissions and their impact on the atmosphere, introduced in the IPCC’s Fifth Assessment Report (AR5). RCP scenarios have a number label (e.g. RCP6.0) indicating how much radiative forcing they

assume in 2100 relative to pre-Industrial times, in Watts per square meter. RCP4.5 and RCP6.0 are intermediate scenarios, whereas RCP8.5 is an extreme scenario with very large future emissions of greenhouse gases.

**REGRESSION:** A statistical method for selecting the coefficients of a linear equation to explain the behaviour of a dependent variable in terms of variations in one or more explanatory variables.

**RICARDIAN ANALYSIS:** A method used in environmental economics named after David Ricardo to estimate the economic impacts of climate change, particularly on agriculture, by making use of the hypothesis that expected changes in the return to future agricultural activity will be capitalized into current land values.

**SCC (Social Cost of Carbon):** An estimate of the net economic damages, measured in present-value dollars, caused by emitting one additional ton of CO<sub>2</sub> into the atmosphere.

**SSP (Shared Socioeconomic Pathway) SCENARIOS:** Different scenarios for future greenhouse gas emissions and their impact on the atmosphere, introduced in the IPCC's Sixth Assessment Report (AR6). Some of the SSP scenarios are analogous to the older RCP scenarios, for purposes of continuity and comparison to earlier climate model assessments.

**TC:** Tropical cyclone.

**TMAX:** The daily maximum surface air temperature.

**TMIN:** The daily minimum surface air temperature.

**TOA:** Top of atmosphere.

**TOXICOLOGY:** The study of the adverse effects of chemical substances on living organisms.

**TREND:** A coefficient, usually estimated using linear regression, representing the slope of a line of best fit through a time series of data, indicating any tendency for the series mean to move up or down over time.

**TSI (Total Solar Irradiance):** The measure of the total amount of incident solar radiation per unit area, including all wavelengths of electromagnetic radiation, that reaches the Earth's atmosphere. Typically shown in units of watts per square meter (W/m<sup>2</sup>).

**UHI (Urban Heat Island):** The tendency for inhabited areas to be warmer than their rural surroundings, due to the replacement of natural land and vegetation with roads, parking lots, buildings, and waste heat sources.

**USHCN:** The U.S. Historical Climatology Network, consisting of quality-controlled temperature and precipitation data from 1,218 surface weather stations.

## 14 ABOUT THE AUTHORS

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**Judith Curry, Ph.D.** is Professor Emerita at the Georgia Institute of Technology, where she served as Chair of Earth and Atmospheric Sciences for 13 years. She is President and co-founder of Climate Forecast Applications Network (CFAN). Curry has a PhD in Geophysical Sciences from the University of Chicago. She has authored or coauthored 192 peer-reviewed papers in atmospheric and climate sciences, two textbooks, and most recently the book *Climate Uncertainty and Risk*. Curry is a Fellow of the American Meteorological Society, the American Association for the Advancement of Science, American Geophysical Union, and a Member of the American Academy of Sciences and Letters.

**The Honorable Steven E. Koonin, Ph.D.** is the Edward Teller Senior Fellow at Stanford's Hoover Institution. He has served as Under Secretary for Science at the Department of Energy (2009-2011), as Chief Scientist for BP (2004-2009), and as a professor at Caltech (1975 – 2004, the last nine years as Vice President and Provost). Koonin is a member of the National Academy of Sciences and the JASON group of government advisors, as well as a Governor of Lawrence Livermore National Laboratory, having served in similar capacities for the Los Alamos, Sandia, Brookhaven, and Argonne National Laboratories. Other prior roles include a University Professor at NYU, a non-resident Senior Fellow at AEI, and a Trustee of IDA.

Koonin has a BS in Physics from Caltech and a PhD in Theoretical Physics from MIT. He authored the 2021 bestseller *Unsettled: What Climate Science Tells Us, What It Doesn't, and Why It Matters*, the 1985 textbook *Computational Physics*, and some 200 peer-reviewed papers in physics and astrophysics, scientific computation, energy technology and policy, and climate science.

**Ross McKittrick, Ph.D.**, is a Professor of Environmental Economics at the University of Guelph in Ontario, Canada. He holds a BA in economics from Queen's University, and an MA and Ph.D. in economics from the University of British Columbia. He has published widely in both economics and physical science journals on topics related to climate change, pollution and public policy. His book *Economic Analysis of Environmental Policy* was published by the University of Toronto Press in 2010. His background in applied statistics has led him to author or coauthor peer-reviewed publications across a wide range of topics in the physical sciences including paleoclimate reconstruction, malaria transmission, surface temperature measurement, climate attribution methodology and climate model evaluation. Professor



McKittrick has made many invited academic presentations around the world, and has testified before the US Congress and committees of the Canadian House of Commons and Senate.

**Roy W. Spencer, Ph.D.**, is a Principal Research Scientist at the University of Alabama in Huntsville. He holds a BS in Atmospheric and Oceanic Science from the University of Michigan, and MS and PhD in Meteorology from the University of Wisconsin -Madison. Spencer's published research has focused on monitoring of weather processes and climate change from Earth-orbiting satellites, as well as using simple physical models for diagnosing climate sensitivity and climate feedbacks. As a NASA Senior Scientist for Climate Studies he served as the U.S. Science Team Leader for the Advanced Microwave Scanning Radiometer (AMSR-E) flying on the Aqua satellite, providing our most accurate global measurements of sea surface temperatures, sea ice, and several other features of the climate system. Along with Dr. John Christy, Spencer developed the first satellite-based technique for global temperature monitoring, for which they received NASA's Exceptional Scientific Achievement Medal and the American Meteorological Society's Special Award.

## 7-6 Extreme weather

### Chapter Summary

*Contrary to popular belief and frequent claims by the media and many political leaders, most types of extreme weather exhibit no statistically significant trends, nor do assessment reports of the IPCC or the NCA claim to have detected them. There has been an increase in hot days in the US since the 1950s, a point emphasized by the IPCC AR6, but numbers are still low relative to the 1920s and 1930s. Extreme convective storms, hurricanes, tornadoes, floods and droughts exhibit considerable natural variability but long-term trends are not detectable. Some increases in extreme precipitation events can be detected in some regions over short intervals but over long periods and at the regional scale the trends do not persist. Wildfire activity has increased in the US in recent decades but has declined globally, and US wildfire activity is down significantly relative to the early 20<sup>th</sup> century. It is also low compared to the estimated natural baseline level. Changes in US wildfire activity are strongly affected by changing forest fire management practices.*

### 76.1 Introduction

High impact weather extremes, usually related to temperature, precipitation and/or excessive high wind, can disrupt infrastructure and therefore endanger human health and wellbeing. The issue is not whether extremes occur, for they are intrinsic to the chaotic climate system. Rather, it is whether there are long-term (decadal scale) changes in the frequency or character of extremes ("detection"), as well as the extent to which such changes and the attendant changes in hazards are caused by anthropogenic emissions of greenhouse gases (~~gases~~ ("attribution"; e.g., IPCC AR6 Seneviratne et al. 2021).

It is naïve to assume that any recent extreme event is caused by human influences on the climate. ~~First, climate~~ Climate is about the statistical properties of weather over decades, not single events. And ~~second~~, there are only about 130 years of reliable observational records that can be analyzed statistically. That brief interval does ~~not begin~~ not begin to contain all of all the extreme events that the climate system can create on its own. Over geologic time the climate system has generated an (essentially) infinite variety of weather patterns and extremes that humans have never observed, and ~~observed~~ and thus are absent from the databases used to determine extreme statistics<sup>1</sup> [see *Perils of short data records* below]. For that reason, ~~attributing an~~ attributing an extreme event unprecedented in the record requires assumptions about the magnitude of natural variations.

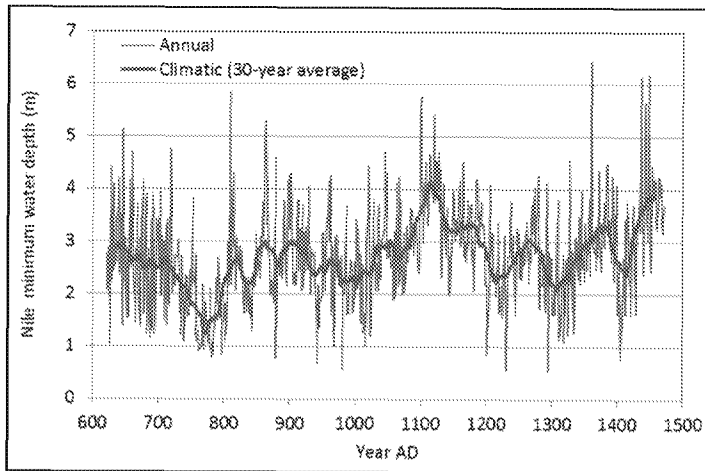
This is especially true for precipitation events. The hydrological literature has long noted the phenomenon of *Long-Term Persistence* (LTP) in rainfall data (Hurst 1951, Cohn and Lins 2005, Markonis and Koutsoyiannis 2015). LTP has a formal mathematical ~~definition~~ definition, but it can be thought of intuitively as the presence of natural variations with strong autocorrelations properties that result in cycle-like behavior on long time scales. The presence of LTP requires long records to accurately estimate variability. Analysis of records short relative to the LTP scale will tend to underestimate variability, therefore overstating the significance of apparent trends and underestimating the likelihood of extreme ~~events~~ (events (Cohn and Lins 2005).

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<sup>1</sup> For example, under the simplest statistical assumptions there is a 37 percent chance that a 100-year event is ~~not~~ NOT present in a given century-long record.

A good example of LTP is the eight-century long record of the annual minimum height of the Nile River observed at Roda Island in Cairo (shown below) in Figure 7, Figure 6.1.1. Since human influences on the global climate were negligible before the 20<sup>th</sup> century, the century-scale variability of the thirty-year average is entirely natural; Egyptians of the seventh and eight centuries would have been incorrect to assume that the worsening drought during that time was the “new normal.”

Commented [A1]: Need to get a good citation for these data



**Figure 7.1.1:** The annual minimum depth of the Nile River near Cairo over more than 650 years from 622 to 1284 A.D. The data, measured in meters, shows a characteristic pattern of year-to-year fluctuations around longer-term trends. Data from [\[HYPERLINK "https://www.itia.ntua.gr/en/docinfo/1351/"\]](https://www.itia.ntua.gr/en/docinfo/1351/)

**Figure 7.1.1:** Nile River discharge [details, source]

With these caveats in mind, we examine the evidence for changes in selected weather and climate extremes. An emergent theme is that emerges when reviewing this topic is the wide gap between public perceptions and scientific evidence. It has become routine in media discussions, coverage, government and private sector discussions, and even in some academic literature to make generalized assertions that extreme weather of all types is getting worse due to GHGs and “climate change.” Yet expert assessments typically have not typically drawn such sweeping conclusions and instead have emphasized the difficulty both of identifying specific trends and establishing a causal connection with anthropogenic forcing.

In the sections to follow we provide excerpts from various IPCC and NCA assessment reports denoting the sources as follows:

**SREX:** The IPCC *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (2012)

**AR6:** The IPCC *Sixth Assessment Report Working Group 1* (2021).

**NCA17:** The US *Climate Science Special Report of the Fourth National Climate Assessment* (2017) Volume I.

**NCA23:** The US *Climate Science Special Report of the Fifth National Climate Assessment* (2023) Volume I.

Note that in the excerpts, *italics* are in the original whereas **boldface** emphasis is ~~is~~ has been added.

## 7.2 Context: detection is not attribution

This chapter is concerned with detection of trends in extreme weather, ~~while Chapter 9.3 looks at~~ considers causal attribution, with Section 9.4 specifically addressing extreme weather. If no trend is detected, then clearly there is no basis for attribution. But even where a trend is ~~observed~~ observed, attribution should not be assumed automatically to follow. Since there is considerable public interest in the question of whether humans are causing extreme weather to get worse, it is useful to recall that AR6 Table 12.12 indicates that, for 34 major weather event and impact types, detection of an anthropogenic signal is asserted with *high confidence* in only four of the 34 weather impact categories, and with *medium confidence* in a further four. The IPCC does not claim to have detected an anthropogenic signal in the remaining 26 categories. Of the four *high confidence* assertions, two are for changes in average temperatures (air and ocean), which are not measures of extreme weather. Also, two of the four *medium confidence* assertions are related to ocean chemistry and are also not related to extreme weather. The IPCC does not assert a detectable human influence on many non-temperature weather features such as wind, precipitation, flooding, and drought.]

**Commented [SK2]:** This needs to appear with Table 12.12 wherever that is placed in our report

## 7.3 Hurricanes and Tropical Cyclones

The AR6 provides the following assessment of tropical cyclones (TCs; used here ~~to be synonymous as a synonym with~~ for hurricanes):

AR6: There is *low confidence* in most reported long-term (multidecadal to centennial) trends in TC frequency or intensity-based metrics due to changes in the technology used to collect the best-track data. (IPCC, 2021)

AR6: It is *likely* that the global proportion of major (Category 3–5) tropical cyclone occurrence has increased over the last four decades . . . There is *low confidence* in long-term (multidecadal to centennial) trends in the frequency of all-category tropical cyclones. (IPCC, 2021)<sup>3</sup>

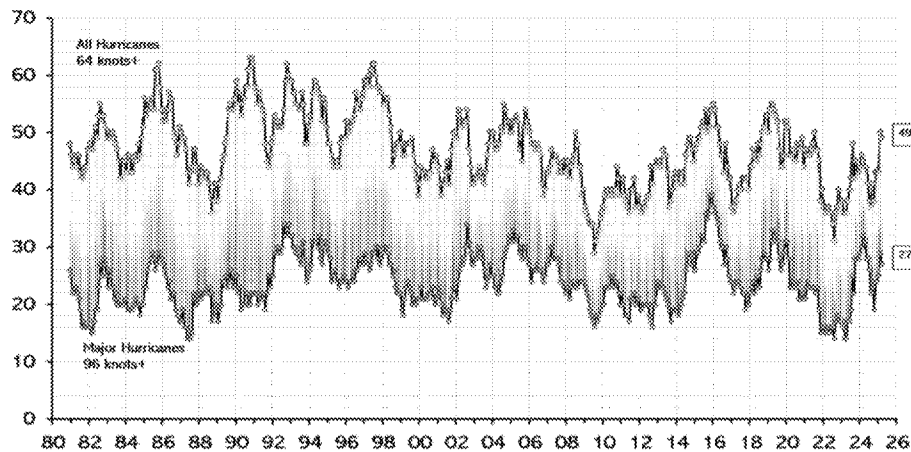
AR6: A subset of the best-track data corresponding to hurricanes that have directly impacted the United States since 1900 is considered to be reliable, and shows **no trend in the frequency of U.S. landfall events**. (IPCC, 2021)

Since 1980, when satellite observations fully covered the global oceans, we have confidence in the numbers of total global hurricanes and major hurricanes (Category 3 and higher). Figure 7.3.1 shows that on average, each year there are about 50 hurricanes, with about 25 reaching major hurricane status (Maue, 2025). There is substantial year-to-year and decadal variability ~~a weak is seen; over the time period, there is a slight decreasing trend in the number of hurricanes and a slight but insignificant increasing trend in the number of major hurricanes. From these two~~ These two trends, it is inferred that there is an overall combine to create an increasing trend of increasing in proportion of percentage of major major hurricanes, relative to the total number of hurricanes.

### Global Major Hurricane Frequency -- 12 month running sums -- @RyanMaue

Updated March 10, 2025

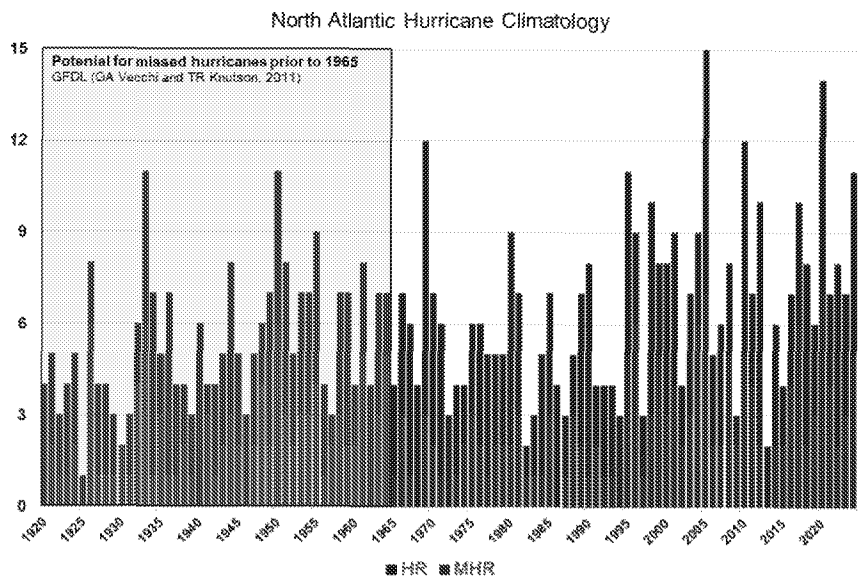
Last 30 years, annual: 45 H | 24 M



**Figure 7-6.3.1:** Global frequency of hurricanes and major hurricanes since 1980.

Global hurricane statistics are dominated by the Northwest Pacific Ocean, which accounts for ~35 percent of total global hurricanes, whereas the Atlantic accounts for ~15 percent of global hurricanes (CSU, 2025). Data in the Atlantic Ocean basin extends further back than in the other ocean basins, and is most relevant to U.S. policy makers.

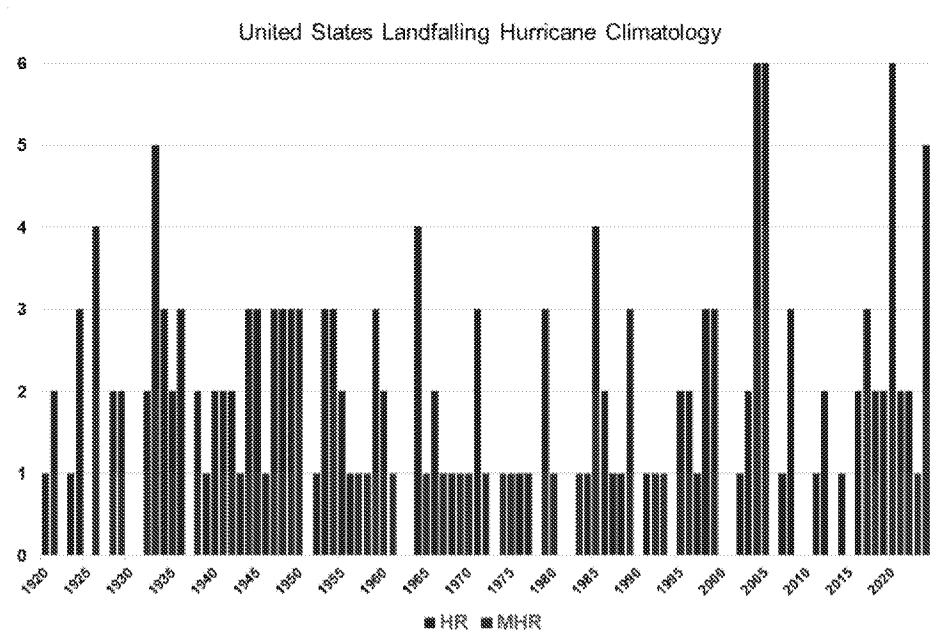
Figure 7-6.3.2 shows the frequency of Atlantic hurricanes (HR) and major hurricanes (MHR; Category 3 and higher) back to 1920. Data prior to 1965 (the onset of satellite observations in the Atlantic, shaded in blue) shows some undercounting, with data prior to 1920 showing substantial undercounting (GA Vecchi and TR Knutson, 2011). All measures of Atlantic hurricane activity show a significant increase since 1970. However, the period from 1971-1994 was a period of exceptionally low activity, with high values of hurricane activity (comparable to the past two decades, even with undercounting) also observed during the 1950's and 1960's, and even in the 1930's.



**Figure 6.3.2:** Atlantic frequency of hurricanes and major hurricanes since 1920. Source (NHC, 2024)

It is seen from Figure 6.3.2 shows that Atlantic hurricanes vary show strongly variations on decadal and multidecadal time scales, in the observed record. These variations are associated primarily with the Atlantic Multidecadal Oscillation (AMO), which is associated with manifest in basin-wide sea surface temperature and sea level pressure fluctuations associated with connected to large scale ocean circulation patterns. The AMO was in its warm phase during 1926-1970 and 1995-present, but in its; the AMO was in its cool phase during 1971-1994. The greatest impact of the AMO has its greatest impact is on the number of major hurricanes (Category 3+). The relationship of the AMO to major hurricane activity in the Atlantic was identified by Goldenberg et al. (2001) to be associated with above normal SSTs and decreased vertical shear associated with in the AMO warm phase AMO (see also Bell and Chelliah, 2006; Klotzbach et al., 2018).

Klotzbach et al. (2018) conducted a comprehensive evaluation of the landfalling hurricane data for the Continental U.S. since 1900. Figure 6.3.3 updates the Klotzbach et al. analysis their analysis through 2024. While the largest numbers of hurricanes are from 2004, 2005 and 2020, there is no statistically significant the overall trend since 1920 is not statistically significant from zero. Figure 6.3.3 also shows the time series for major hurricane landfalls (Category 3-5). The largest year in the record is 2005, with 4 major hurricane landfalls. However, there were no major hurricanes striking the U.S. during the period from 2006 through 2016, there were no major hurricanes striking the U.S., which is the longest such period in the record since 1920.



**Figure 76.3.3:** US landfalling frequency of hurricanes and major hurricanes since 1920. Source (NOAA HRD(a), 2024)

Substantial interannual to multidecadal variability in U.S. landfall activity is seen Figure 76.3.3. Klotzbach et al. (2018) examined how the landfall counts vary with ENSO (El Niño versus La Niña) and the warm versus cold phases of the Atlantic Multidecadal Oscillation (AMO).

Villarini et al. (2012) provide an analysis of U.S. hurricane landfalls back to 1878. While it is possible that some landfalls were missed in the late 19<sup>th</sup> century owing to sparsely populated regions on the Gulf Coast, it is remarkable that the highest year in the entire record, is 1886, with 7 landfalls, is 1886.

Table 76.3.1 shows the 10 strongest hurricanes (plus ties) to make U.S. landfall. Of the hurricanes that have made landfall with sustained winds greater than 150 mph, only one has occurred in the 21<sup>st</sup> century.

**Table 76.3.1** Strongest hurricanes to make landfall along the US coast. Source (NOAA HRD(b), 2024)

| Rank | Year | Landfall Wind (MPH) | Name        |
|------|------|---------------------|-------------|
| 1    | 1935 | 185                 | "Labor Day" |
| 2    | 1969 | 175                 | Camille     |
| 3    | 1992 | 165                 | Andrew      |

|   |      |     |               |
|---|------|-----|---------------|
| 4 | 2018 | 160 | Michael       |
| 5 | 1856 | 150 | "Last Island" |
| 5 | 1886 | 150 | "Indianola"   |
| 5 | 1919 | 150 | -----         |
| 5 | 1932 | 150 | "Freeport"    |
| 5 | 2004 | 150 | Charley       |
| 5 | 2020 | 150 | Laura         |
| 5 | 2021 | 150 | Ida           |
| 5 | 2022 | 150 | Ian           |

While it has long been hypothesized that a rising global sea surface temperature would cause an increase in hurricane intensity, ~~has long been hypothesized to occur as global sea surface temperatures increase~~, identification of any significant trend in the hurricane data is hampered by a short data record and substantial natural variability.

In summary, analyses of both global and regional variability and trends of hurricane activity provide the basis for detecting changes and understanding their causes. The relatively short historical record of hurricane activity, and the even shorter record from the satellite era, is not sufficient to assess whether recent hurricane activity is unusual relative to the background natural variability. Atlantic hurricane processes are influenced substantially by the natural modes of ocean circulation variability in the Atlantic, notably the Atlantic Multidecadal Oscillation.

#### 76.4 Temperature extremes

The AR6 assessment focused on the period after 1950 and reported increasing trends in heatwave frequency and intensity. ~~However, The the NCA17 however~~ noted that heatwave activity in the US reached a peak in the 1930s.

AR6: "It is *virtually certain* that hot extremes (including heatwaves) have become **more frequent** and **more intense** across most land regions since the 1950s, while cold extremes (including cold waves) have become less frequent and less severe" (SPM, A3.1)

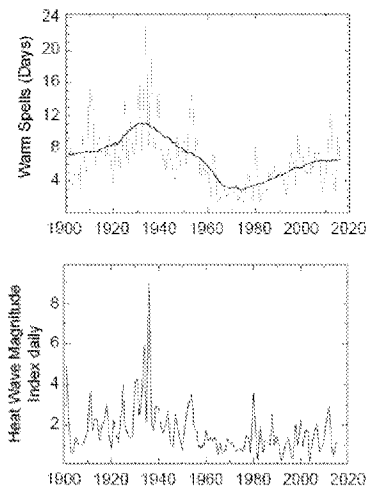
AR6: "In North America, there is very robust evidence for a *very likely* increase in the intensity and frequency of hot extremes and decrease in the intensity and frequency of cold extremes for the whole continent, though there are substantial spatial and seasonal variations in the trends. Minimum temperatures display warming consistently across the continent, while there are more contrasting trends in the annual maximum daily temperatures in parts of the USA." (Chapter 11, p 1550)

NCA17: "Changes in warm extremes are more nuanced than changes in cold extremes. For instance, the warmest daily temperature of the year **increased** in some parts of the West over the past century, but there were **decreases** in almost all locations east of the Rocky Mountains. In fact, all eastern regions experienced a net **decrease**, most notably the Midwest (about 2.2°F [1.2°C]) and the Southeast (roughly 1.5°F [0.8°C])." (pp. 190-191)

NCA17: "Since the mid-1960s, there has been only a very slight increase in the warmest daily temperature of the year (amidst large interannual variability). Heat waves (6-day periods with a maximum temperature above the 90th percentile for 1961–1990) increased in frequency until the mid-1930s, became considerably less common through the mid-1960s, and increased in frequency



again thereafter. As with warm daily temperatures, **heat wave magnitude reached a maximum in the 1930s.**” (pp. 190-191)



**Figure 6.4.1: US Heat waves since 1900.** Source: NCA17 Figure 6.4

#### 6.4.1 Temperatures in the US are becoming less extreme

Daily maximum temperatures in the warm season (TMax, May-Sep) and daily minimum temperatures in the cold season (TMin, Dec-Mar) are available beginning in Dec 1898 (126 years). The dataset consists of 1,211 CONUS stations designated as United States Historical Climate Network or USHCN stations (see [Figure 6.4.2](#); Quinlan et al. 1987, Karl et al. 1990). These stations were selected by NOAA as having the fewest problematic issues with gaps, station moves and instrument changes. Where gaps still exist, nearby stations (bias-corrected) were merged so that the median volume of data available for a station is 98%. Although there are certainly errors in the dataset, with over 1,000 stations we can have relatively high confidence in any underlying signal that might be discovered.

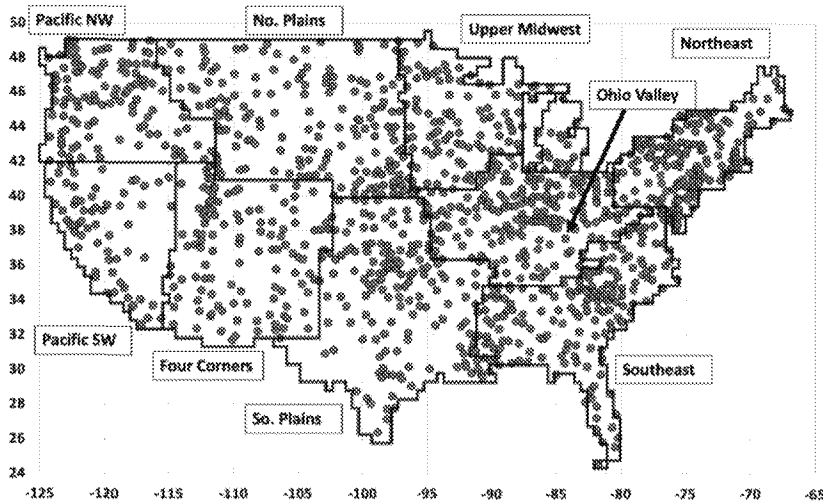
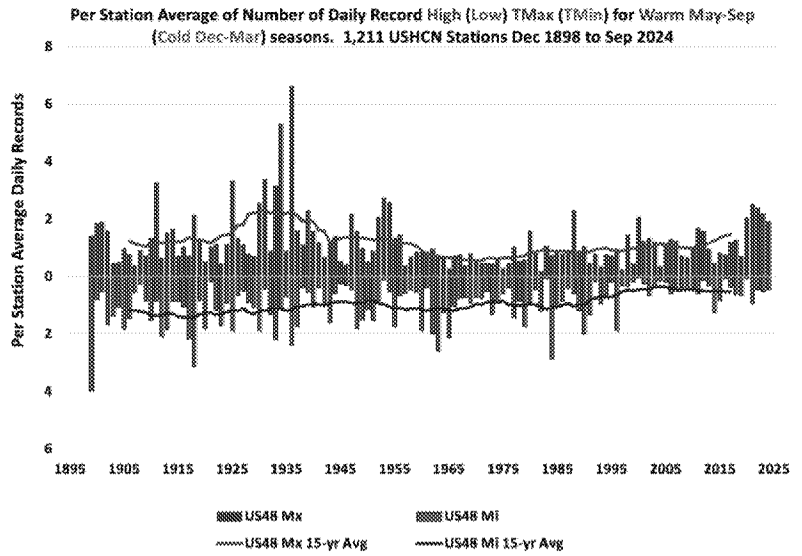


Figure 7. Figure 6.4.2 Locations of USHCN temperature stations. Source: USHCN.

We begin with the question of whether the occurrence of daily record high or low temperatures has changed since Dec 1898. Each warm-season has 153 days (1 May to 30 Sep) and each cold-season has 122 days (1 Dec to 31 Mar). For each station and day, we calculated the year in which the record highest (lowest) temperature occurred. With 126 years of observations, if there were no temperature trends over time, the expected number of records for TMax would be 1.21 ( $=153/126$ ) per station per year and for TMin 0.96 ( $=122/126$ ) per station per year.

Figure 76.4.3 indicates shows the observed distribution in time of the occurrence of these extreme events. There is a common feature in many metrics of warm-season extremes in the CONUS - the exceptional heat of the 1920s and especially the 1930s, peaking in 1936. On a per-station average, 60% of the TMax records and 59% of the TMin records occurred in the first half of the period (1899-1961).



**Figure 7.4.3** Number of daily record High (red) and Low (blue) temperatures for warm and cold seasons in the CONUS. The lines represent the 15-year running, centered average. Source: 1,211 USHCN stations supplemented as needed to achieve a minimum of 92% of observations in the 126-year period since Dec 1898.

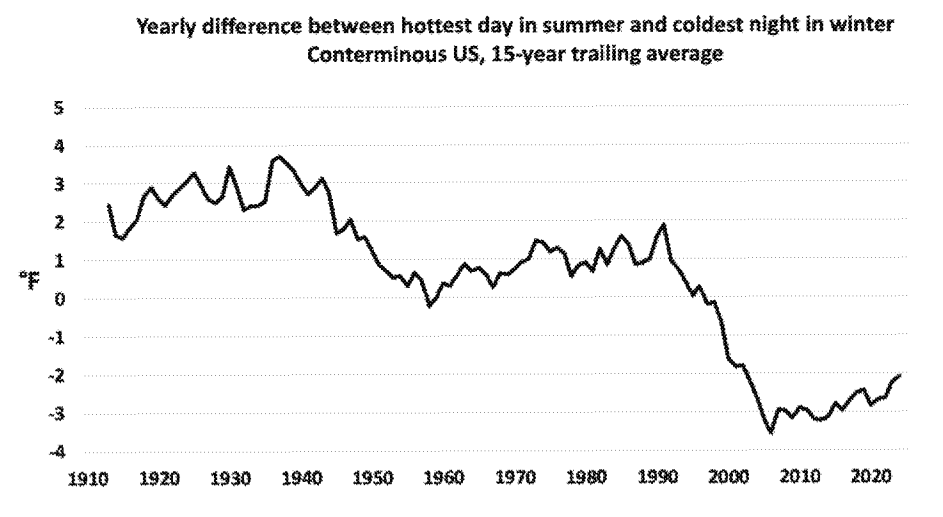
The results indicate a common feature in many metrics of warm-season extremes in the CONUS – the exceptional heat of the 1920s and especially the 1930s, peaking in 1936. On a per-station average, 60% of the TMax records and 59% of the TMin records occurred in the first half of the period (1899–1961).

On the cold side, the Valentine’s Day Arctic outbreak in Feb 1899 stands as the most extensive cold extreme experienced by the CONUS, with 1917 in 2<sup>nd</sup> place. The frequency of cold records has declined, especially over the last quarter of the period in which only 13% of the extreme cold events were measured. In contrast, 25% of the extreme TMax records were achieved in the last quarter, in accordance with statistical expectations. These general features have been noted in past assessments (see above, IPCC AR6, NCA17). Combining the two records the overall reduction in numbers of both cold and hot extremes over the past century indicates a climate less prone to extremes.

This pattern is also shown in Figure 7.4.4. For each station and for each year the hottest warm season and coldest cold-season temperatures were calculated. Then the differences between these were computed by station and geographically-averaged over all stations, thus yielding an annual measure of the expected range of local extreme temperatures for each year. Figure 7.4.4 shows the 15-year trailing average of this measure, which has clearly declined over the past century.

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**Figure 6.4.4.** 15-year trailing average of the difference each year of each station's hottest warm-season TMax and coldest cold-season TMin relative to the long-term average. Source: USHCN, author calculations.

The average difference for each station between the hottest summer TMax and coldest winter TMin has declined by about 5°F in the past 126 years. The decline is due mostly to warmer winter TMin, but a decline in the magnitude of summer TMax is also a factor. The rise in TMin has been strongly related to the growing presence of manufactured surfaces around the weather stations over the last 100+ years (the so-called urban heat island effect; Spencer et al. 2025).

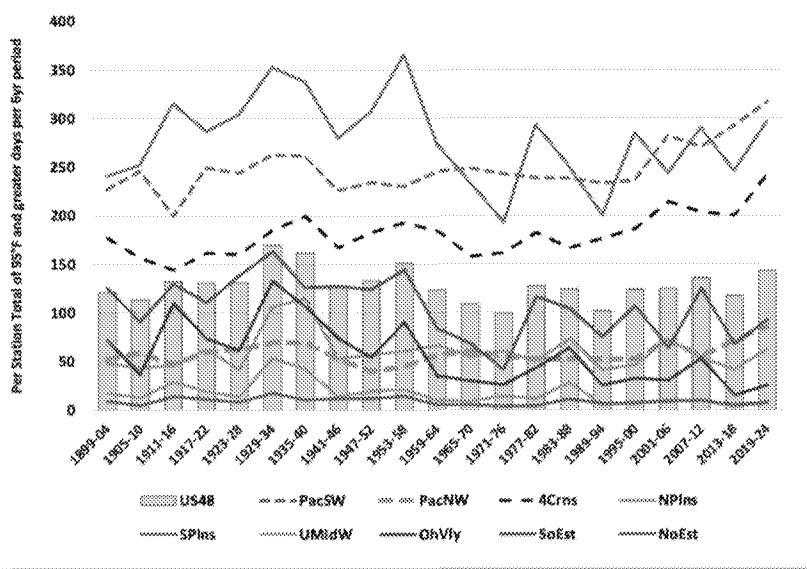
In summary, while temperature extremes are regularly experienced in the U.S. and attract a great deal of media attention, long term records show the US climate has become less extreme over time (milder) when measured in terms of the range between warm season maxima and cold season minima.

#### 6.4.2 Exceedances of a heat threshold

Under the heading of "The Risk of Temperature Extremes is Changing", the most recent US National Climate Assessment report (NCA23) notes the increase in a threshold metric of number of days at or above 95°F, stating,

"The western US has been particularly affected by extreme heat since the 1980s ..., experiencing a larger increase in days over 95°F, as would be expected given the greater warming in that region relative to the eastern US. Several major heatwaves have affected the US since 2018, including a record-shattering event in the Pacific Northwest in 2021."

Are the occurrences of 95°F days changing? In a climate as varied as that of CONUS, threshold statistics can be misleading. A region with many stations that have near 95°F TMax average temperatures in the summer might see large swings in the metric when only small changes in average temperature occur. Elsewhere with stations that either rarely or virtually always achieve 95°F TMax temperatures, a small change will not have much impact on the results, much at all. In the past 126 years, the average CONUS station experienced 129 days exceeding 95°F per 6-yr period, but the regional values range from 278 in the Southern Plains to 9 in the Northeast. Thus, one needs to view such threshold analyses must be interpreted with caution.



**Figure 76.4.5.** Total number of days  $\geq 95^{\circ}\text{F}$  in 6-yr periods, US 48 (bars) and regions (lines). Interval is 6-years as this is divisible into 126. Source: USHCN, author calculations.

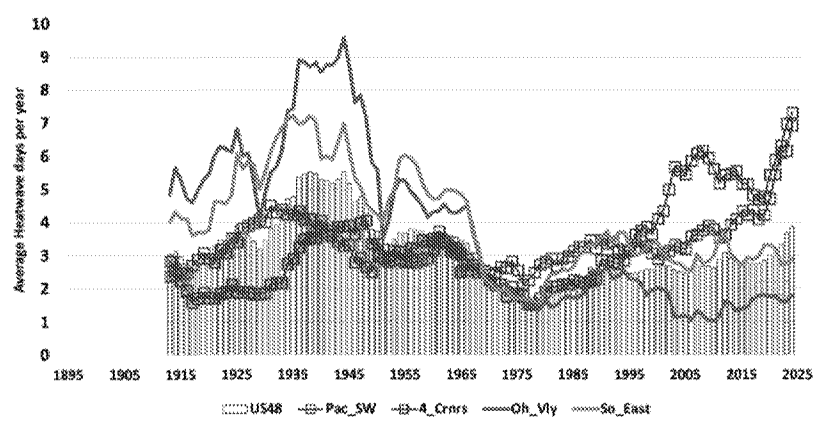
In Figure 76.4.5 we see shows that only three of the nine regions, all in the West, have experienced upward trends in the number of 95°F or hotter days (dashed lines). The CONUS as a whole has not, and the other six regions have experienced declines.

The Pacific NW heatwave of 2021 is referenced in the NCA23 quote will be, an event we examined more closely in Section 98.4. The evidence indicates that it was a single, unprecedented event in the record, not part of a pattern of increasing extreme heat. For example, the 5-day average tropospheric grid-point temperature anomaly over the Pacific NW during that event was  $+10.8^{\circ}\text{C}$ , the most extreme Northern Hemisphere grid point summer anomaly in the 46 years from over 4 million grid values. In contrast, the global temperature anomaly during that time was virtually zero ( $+0.03^{\circ}\text{C}$ , Mass et al. 2024).

The heading "The Risk of Temperature Extremes is Changing" WHERE IS THIS HEADING FROM – Perhaps NCA23? suggests pervasive positive trends are now being observed in threshold temperatures, on a widespread basis, but that is not evidenced in the figures above.

#### 6.4.3 Heatwaves

Heatwaves (consecutive days that exceed an extreme threshold) have a greater societal impact than a single daily record temperature. We measure "Heatwave Days" here as the count of all days in May-Sep each year that exceed the 90<sup>th</sup> percentile for that day and that lie within a period of at least six consecutive days. This is equivalent to the method used in NCA17, except that the reference period here is the entire record 1899-2024 while NCA17 truncated the reference period to 1961-1990, which was a cool period. That truncation boosts positive results (days exceeding the 90<sup>th</sup> percentile) in periods warmer than the reference period, especially starting in 1960 and moving to the present (see *Urban Influences* below).



**Figure 6.4.6** 15-year trailing average of number of heatwave days per year per station in the CONUS (bars) and four regions: Pac\_SW (purple squares, CA, NV), 4\_Crnrs (red squares, AZ,NM,UT,CO), Oh\_Vly (blue, MO, IL, KY, TN, IN, OH, WV) and So\_East (green, MS, AL, GA, FL, SC, NC, VA).

Figure 6.4.6 indicates again the excessive heat of the first half of the 20<sup>th</sup> century, primarily in the eastern two-thirds of the nation, for example as seen in the regional values for the Ohio Valley and the Southeast as examples. The West has seen a recent increase of heatwave days and the two regions with the highest number are shown; the Pacific Southwest and the Four-Corners (NCA23). This indicates that the background warm season circulation favored heatwaves in the eastern portions of the country in the first half of the 20<sup>th</sup> century, but in the 21<sup>st</sup> century the patterns have favored heatwaves in the West. For CONUS as a whole, heatwaves are no more common today than they were a century ago, consistent with the upper panel of our Figure 6.4.1 taken from NCA17.

Of interest here is the regional variation of this metric. This metric varies significantly with region. The four northern regions (Pacific NW, Northern Plains, Upper Midwest, and Northeast) on average experience 15 to 27 heatwave days per 15-year period. In contrast, the five southern regions (Pacific Southwest, 4-Corners, Southern Plains, Ohio Valley and Southeast) see 37 to 54 such days, essentially twice as many. This suggests the summer circulation pattern is more prone to stationary events in the southern regions while transient systems in the northern regions are more common and thus cut short these potentially longer events.

#### 7.4.4 Urban influences

The NCA23 directs readers to the website [\[HYPERLINK "https://www.globalchange.gov/indicators/heat-waves"\]](https://www.globalchange.gov/indicators/heat-waves) (USGCRP 2023) to view a figure showing the number of urban heatwaves by decade from the 1960s, as shown below which we reproduce as Figure 6.4.7.

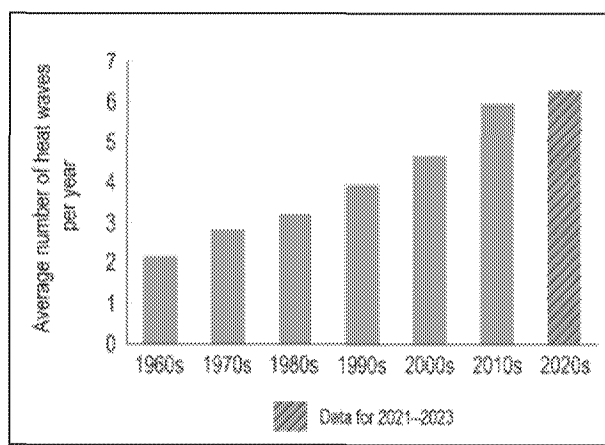


Figure 6.4.7: Average number of urban heatwaves per year for 50 large U.S. metropolitan areas. From [\[HYPERLINK "https://www.globalchange.gov/indicators/heat-waves"\]](https://www.globalchange.gov/indicators/heat-waves)

The figure shows a monotonic increase in each decade from 2 occurrences per year in the 1960s to 6 in the 2020s. The definition of a heatwave used is an unusual but practical measure of human discomfort - a period of at least 2 consecutive days when the minimum apparent temperature (combination of temperature and humidity) exceeds the 85<sup>th</sup> percentile. Note too, the dataset is limited to the 50 largest U.S. cities.

These increasing values since 1960 presented in USGCRP (2023) are entirely reasonable, but are unrelated to not informative about the influence of GHG emissions for at least two reasons. ~~Also First, as shown in Figures 6.4.1 and 6.4.6, the 1960s was the coldest decade and 1970s the second coldest decade since the 1910's, so this starting date preconditions the time series to show increases. Second, post-1960 urbanization in these cities is a major factor in the rise of TMin relative to co-located TMax and relative to TMin at nearby rural stations. Also, the 1960s was the coldest decade and 1970s the second coldest decade since the 1910's, so this starting date preconditions the time series to show increases. This does not dismiss the real rise in nighttime temperatures in major U. S.~~

cities and the societal impacts associated with these changes. However, we note for a variety of reasons, that summer TMax (especially in rural areas) serves as a better response variable metric for detecting potential changes in heatwaves influenced by changes in the background climate due, for example, to increasing GHGs (Christy et al. 2009). For the CONUS as a whole, the evidence in this section suggests GHG emissions have had little-to-no effect on heatwaves.

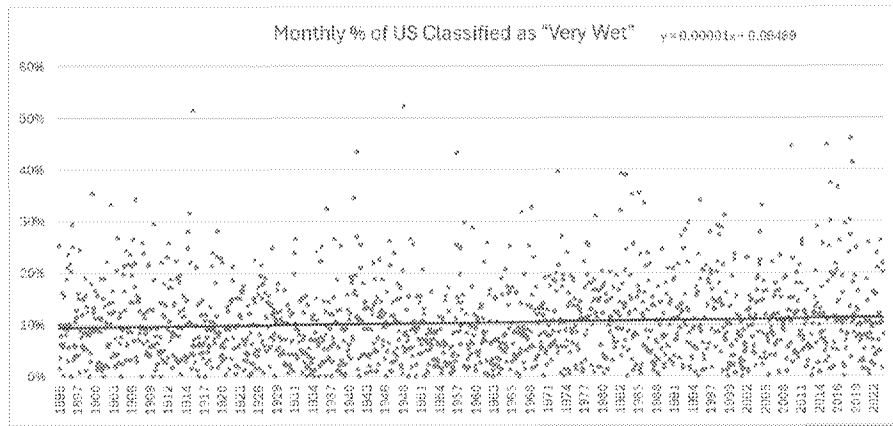
## 6.5 Extreme precipitation

The IPCC AR6 assessed that an increase in heavy precipitation has been observed in data starting in the 1950s.

AR6: “The frequency and intensity of **heavy precipitation events have increased** since the 1950s over most land area for which observational data are sufficient for trend analysis (high confidence).” (SPM A3.2)

AR6: “In North America, there is robust evidence that the **magnitude and intensity of extreme precipitation has very likely increased** since the 1950s. Both [one-day maxima] and [5-day maxima] have significantly increased in North America during 1950-2018” (Chapter 11, p. 1560)

However other data sources indicate less evidence of increasing extreme precipitation when examined over a longer time scale. Figure 6.5.1 shows that US long term data from NOAA (1895-2023) shows has an insignificantly increasing tendency toward extreme wetness (+0.001% per year)



**Figure 6.5.1:** Long term US wetness (%). Source: NOAA [ [HYPERLINK "https://www.ncei.noaa.gov/access/monitoring/uspa/wet-dry/0"](https://www.ncei.noaa.gov/access/monitoring/uspa/wet-dry/0) ]

The US National Climate Assessments (NCA17, NCA23) have highlighted an increase in the occurrence of the heaviest precipitation events (defined in different ways) primarily in the eastern half of the CONUS, especially the Northeast, when starting the analysis in either 1901 or 1958. Interestingly, the regional variations indicate that the largest increases in extreme precipitation



events are in the Northeast and the smallest in the West, a pattern counter to the changes in temperature extremes.

McKittrick and Christy (2019) examined long-term and consistent station observations of extreme daily precipitation to test some of these NCA claims for the Southeast and West Coast. When the time series were extended back in time (as far as 1872 in some cases) or when starting later (1978), there were no significant trends for either region.

~~For this report we updated these~~ These findings have been updated for this report with similarly constructed observations from 29 stations on the CONUS Pacific Coast (1893ff from San Diego CA to Blaine WA) and 24 stations in the humid Southeast (1872ff from Austin TX to Washington DC), also adding 24–27 stations in the Northeast (1888ff from Buffalo NY to Gardiner–Eastport ME). The locations are shown in ~~Figure 7~~ Figure 6.5.2. The results of applying the analysis of McKittrick and Christy (2019) were as follows for each region, then followed by further explanation.



**Figure 5.2:** Locations of precipitation monitoring stations used in this report. Green: Pacific coast  
Blue: Northeast. Red: Southeast.

#### *Pacific Coast heavy rainfall events*

- Average precipitation trend is significant (downwards) in Astoria OR; insignificant elsewhere.
- The trend in rainfall variance is positive and significant in Big Sur CA; insignificant elsewhere.

- The trend in daily maximum precipitation is positive and significant in Aberdeen WA and Big Sur CA and negative and significant in Newport OR (insignificant elsewhere).
- Averaged over all stations in the region, none of these three trend parameters is statistically significant.

The Pacific Coast receives considerable precipitation from Atmospheric River (AR) events which often last more than a day or two (e.g., Gershunov et al. 2017, Pan et al. 2024). The worst-known such-series of such events in recent history was the so-called ARkStorm that occurred between December 1861 and January 1862; ~~it, which~~ dumped nearly 10 feet of rain in parts of California and submerged the entire Central Valley for weeks under as much as 15 feet of water (Brewer 1930, Null and Hulbert 2007). Additionally, Paleoclimate research has found six megastorms more severe than 1861–1862 in California during the last 1800 years, occurring at intervals of 300 years or so (Porter et al. 2011).

SIDEBAR: Perils of short data records  
 San Francisco provides a good case study of the limitation of using short historical samples to characterize natural variability of extreme events. Suppose we use a 130-year sample of daily San Francisco precipitation from 1895 to 2024 and we look for 3-day, 5-day, 14-day and 30-day rainfall records. The results are as shown in Table 7.2.

| Event  | Record (inches) | Year |
|--------|-----------------|------|
| 3-day  | 6.94            | 2023 |
| 5-day  | 8.55            | 2023 |
| 14-day | 12.62           | 2023 |
| 30-day | 18.93           | 1998 |

Table 7.2: Extreme rainfall records, San Francisco, 1895-2024.

The records all cluster in the more recent ~~data years~~. 2023 appears to be an exceptional year and since it is near the end of the sample, it might suggest that the climate has shifted into a more hazardous state, perhaps as a result of human influences. [Note: "2023" indicates the event occurred in the water-year of Aug 2022 to Jul 2023.]

But the picture is very different if we use a sample that begins ~~45 years earlier, in 1850~~. Table 7.3 shows that the record-setting events all happened in the 1860s. Furthermore 2023 is now not even in 2<sup>nd</sup> place but falls to 3<sup>rd</sup> or 4<sup>th</sup> place. Also, comparing the records of the two charts the extreme precipitation events in 1862 and 1867 involved considerably more rainfall than the 1998 and 2023 events, with 14- and 30-day totals about 50 percent higher.

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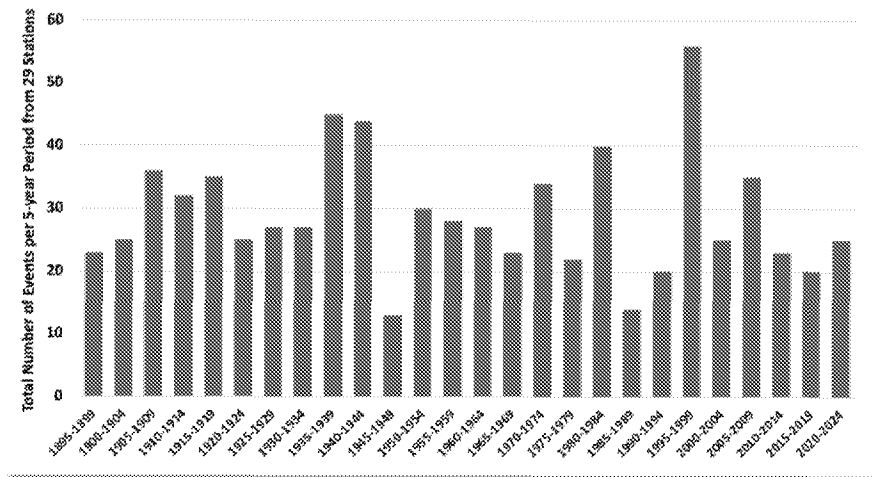
| Event  | Record (inches) | Year | Rank of 130-yr extreme |
|--------|-----------------|------|------------------------|
| 3-day  | 8.85            | 1867 | 3                      |
| 5-day  | 9.80            | 1867 | 3                      |
| 14-day | 19.05           | 1862 | 4                      |
| 30-day | 28.25           | 1862 | 2                      |

Table 7.3: Extreme rainfall records, San Francisco, 1850-2024.

The range of natural variability is made even more remarkable when paleoclimate evidence is examined. Porter et al. (2011) discovered that in the past 1,800 years at least six megastorms were more intense than the devastating 1861-62 ARkStorm that struck the region. Evidently such extreme events, “unprecedented” in our 1895-2024 sample, have impacted the region about every 300 years, though not since 1895.

This example illustrates the limitations of using relatively short climate periods (~130 years) to assess the character and range of natural variability in general and of extreme events in particular. Accurate representation of the full range of natural variability is necessary for any attribution analyses (see 86.4). Infrastructure planners, emergency management institutions and attribution scientists would understand the significant mischaracterization of the magnitude of a future extreme if based only on the last 130 years. In this case, a single time-sample of 130 years provides an underestimation of the extreme value by up to 50% determined when adding only 45 more years of observations. Compared to millennial-scale paleoclimate evidence, an even greater underestimation would occur. An important lesson is that the climate can deliver great surprises on its own, even without human influences.

We examine occurrences of 5-day deluges as follows. Taking the Pacific coast as an example, in a 130-year span there contains are 26 5-year intervals (pentades). At each location we computed the 5-day precipitation totals throughout the year and selected the 26 highest values across the sample. A single year may have more than one of the 26 heaviest. Each of those can be thought of as 1-in-5yr events. If there are no trends in precipitation, then the total number of these events across all stations should be evenly spread out over the years. In Fig. 76.5.3 we show the distribution in time of these events for the Pacific coast. The deluges associated with the massive 1997-98 El Niño event are readily apparent. While erratic, as is typical of these types of such precipitation metrics, there is no indication of a tendency to become more frequent over time.



**Figure 7.5.3.** The time distribution by 5-year periods of the 26 heaviest (1-in-5 yr) occurrences for 29 stations on the Pacific coast.

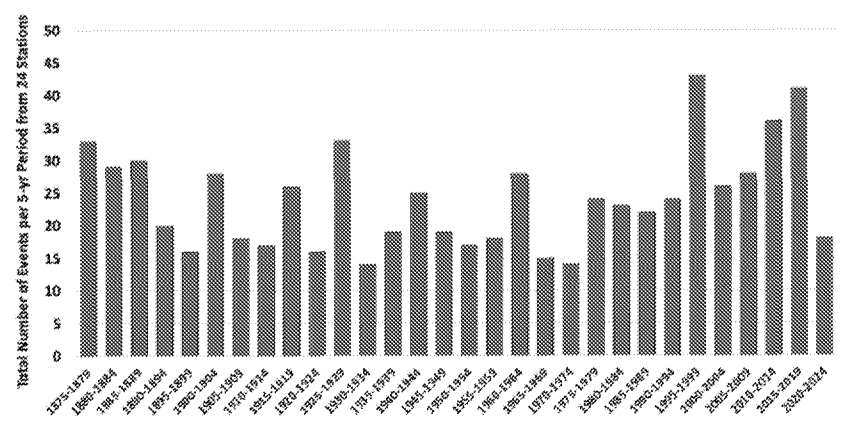
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**Commented [A7R6]:** They're better presented individually esp since we go into additional detail on the NE region

#### *Southeast heavy rainfall events*

- The trend in average precipitation is positive and significant in Mobile AL and Quitman GA, and insignificant elsewhere.
- The trend in rainfall variance is positive and significant in Mobile AL, insignificant elsewhere.
- The trend in daily maximum precipitation is positive and significant in Vicksburg MS and Norfolk VA, and insignificant elsewhere.
- Averaged over all stations in the region none of these three trend parameters is statistically significant

Figure 7.5.4 shows the same calculation for the last 150 years in the Southeast humid zone. The temporal pattern of 5-day totals of the 1-in-5yr heavy events is generally unremarkable, though a cluster of higher values appears in 1995 to 2019. The increase in those years is due largely to the 4 northeastern-most stations of Wilmington NC, Weldon NC, Washington DC, and Norfolk VA. This confirms the pattern indicated in NCA4-NCA17 and NCA5-NCA23 -- of a tendency for an increasing frequency of heavy events due to a temporal clustering of tropical storms from eastern NC to Maine discussed below. Otherwise, the remaining 20 stations show an unremarkable temporal distribution of heavy events.



**Figure 7.5.4.** As in Fig. 7.5.3 but for the heaviest 30 (1-in-5yr) events for 24 stations in the humid Southeast from Austin TX to Washington DC in 5-year bins for 1875-2024.

#### *Northeast heavy rainfall events*

- The trend in average precipitation is positive and significant in 9 of 21 locations and also in the regional average, overall.

- The trend in rainfall variance is positive and significant in Portland ME, Albany NY and Buffalo NY, ~~but~~ insignificant elsewhere.
- The trend in daily maximum precipitation is positive and significant in Portland ME and Gardiner ME, ~~but~~ insignificant elsewhere.
- ~~When averaged over all stations in the region, there is no statistically significant trend in either the precipitation variance or maximum. Averaged over all stations in the region the trend parameters for variance and maximum precipitation are not statistically significant.~~

Fig. 76.5.5 shows the same calculation for the last 135 years in 24-27 stations in the Northeast (including Montreal Canada). We use 3-day totals here as this produced the largest temporal variations in time. In this region, 72% of the ~~events~~ events occur during June to October and are dominated by tropical incursions of hurricanes, tropical storms, or tropical storms that transition to extratropical systems. According to NCA17 and NCA23 this region experienced the largest increases in extreme events, so it shall be examined more closely it merits a closer examination.

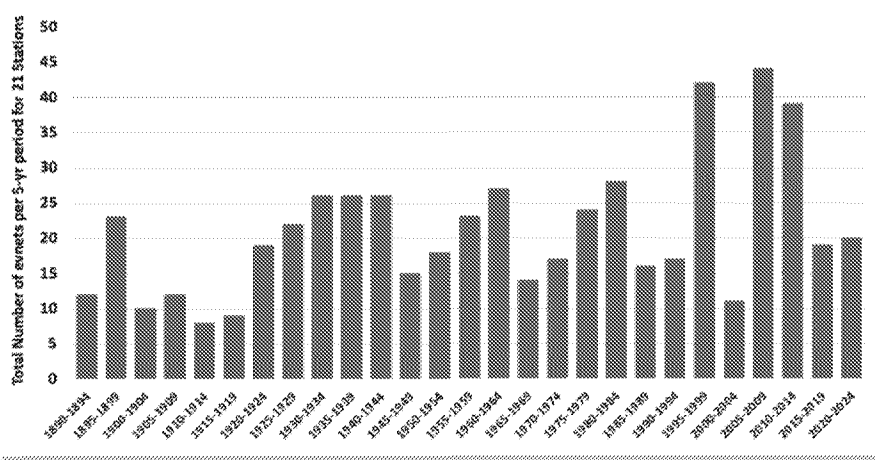
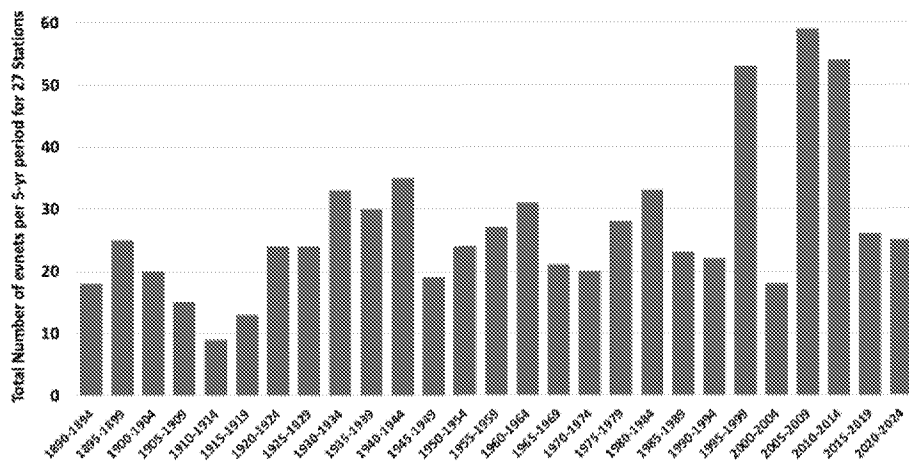


Figure 7. Figure 6.5.5. As in Fig. 6.5.3 but for the heaviest 27 (1-in-5yr) 3-day precipitation events for 21 Northeast stations from NY to ME, including Montreal.

There is a noticeable clustering of extreme events from 1995 to 2014. Howarth et al. (2019) examined a similar region as in Fig. 7.5.5 that includes PA and NJ and reported significant differences between two 18-year periods, 1979-96 and 1997-2014, of various precipitation extremes, including. They reported a dramatic increase (317%) increase in 24-hr events exceeding 6 inches, while we find a 51% increase. Using the information in Fig. 7.5.5 over the same years, we find a 51% increase in the frequency of heavy events. However, Figure 7. Figure 6.5.5 shows that the frequency drops sharply after 2014, returning to the long-term average in the subsequent pentades over the next decade.

again illustrating the perils of drawing conclusions from short-term trends in highly variable metrics. It was thus unfortunate that Howarth et al. sample ended in 2014.

Also the high percentage increase in the Howarth et al. sample is associated with small numbers at relatively few locations: there were only 6 in the first period and 25 in the second across 58 stations. Most of the stations did not record such an event. If there is a region-wide increase in heavy events, it should be seen in the average across all stations. Figure 6.5.6 shows the average precipitation in the 1-in-5 yr events across the NE. The trend is only +0.02"/decade. The highest amount, 1935-39, includes the Great New England Hurricane of 1938, one of the rare major (Category 3 or higher) hurricanes to strike the region. The results in Figs. 6.5.5 and 6.5.6 thus suggest that though there was a surge in the number of events at a few locations during the 1995 to 2014 interval, there was no regional pattern and pattern was not region-wide nor did the change did not persist after beyond 2014.

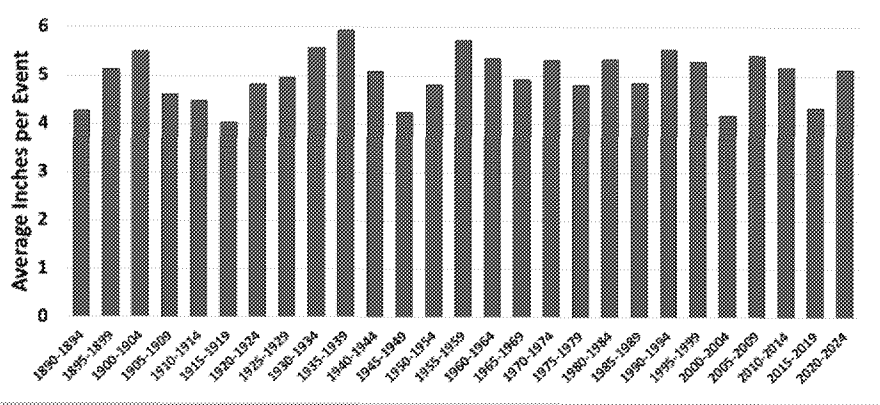
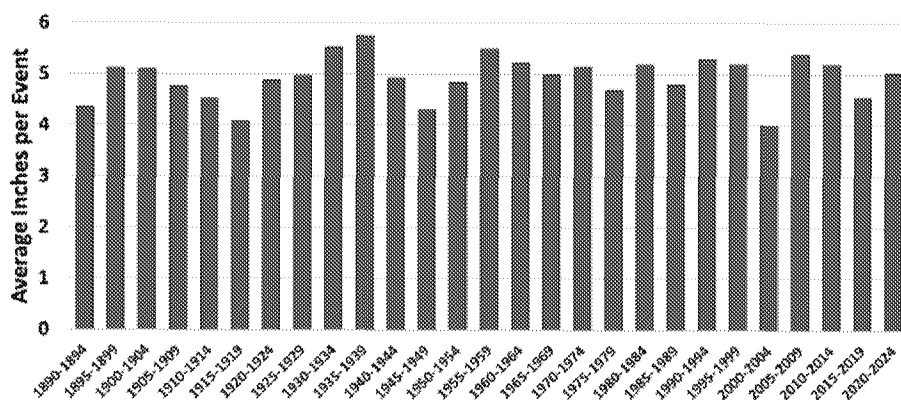


Figure 6.5.6. Average amount of precipitation falling in the 1-in-5yr events for the NE stations.



Jong et al. (2024) document the increase of tropical influences on precipitation events in the Northeast since 1959 and concluded, “The autumn extreme precipitation trend over the Northeast US is primarily attributed to tropical cyclone-related events since the 1990s.” The question then becomes: was the temporal clustering of tropical systems in 1997-2014 which affected the Northeast a response to increasing GHGs (see Chapter 9 Attribution)? Jong et al. examined CMIP-6 model output which suggests that there will be fewer such systems in the 21<sup>st</sup> century but that the intensity of the rainfall events might increase. This conjecture is not seen in Fig. 7.5.6 where the amount-per-event has remained steady over the 135-year period.

There is some evidence to indicate the heaviest rainfall events may be redistributed due to the impact urban infrastructure has on the local weather (e.g., Pielke Sr. et al. 2011, Zhang et al. 2018, Yang et al. 2024). Yang et al. state, “Cities that experience compact development tend to witness larger increases in extreme rainfall frequency over downtown than their rural surroundings, while the anomalies in extreme rainfall frequency diminish for cities with dispersed development.” While this is an important insight to consider, the effect on the specific stations used in this analysis is unknown, or at least not detectable in Fig. 7.5.6.

In summary, while some regions show short-interval apparent increases in extreme precipitation events, in some regions over short intervals can be found in the record, the evidence from analysis of long term, nationwide historical records does not support the claim that extreme short-duration rainfall events are becoming more frequent or intense.

## 7.6 Tornadoes

AR6: [O]bservational trends in tornadoes, hail, and lightning associated with severe convective storms are **not robustly detected** due to insufficient coverage of the long-term observations. There is *medium confidence* that the mean annual number of tornadoes in the USA has remained relatively constant. (Chapter 11, section 11.7.3, p. 1594)

As noted, there is no evidence of trends in US tornadoes or extreme convective storms.

## 7.7 Flooding

Changes in floods were assessed as follows:

AR6: “The SREX **assessed low confidence for observed changes in the magnitude or frequency of floods** at the global scale. This assessment was confirmed by the AR5 report. The SR15 found increases in flood frequency and extreme streamflow in some regions, but decreases in other regions. . . [H]ydrological literature on observed flood changes is heterogeneous, focusing at regional and sub-regional basin scales, making it difficult to synthesise at the global and sometimes regional scales.” (Chapter 11.5)

AR6: “[T]he seasonality of floods has changed in cold regions where snowmelt dominates the flow regime in response to warming (*high confidence*). Confidence about peak flow trends over past decades on the global scale is **low**.” (Chapter 11.5)

NCA17: “Trends in extreme high values of streamflow are **mixed** across the United States. Analysis of 200 U.S. stream gauges indicates areas of both increasing and decreasing flooding magnitude **but does not provide robust evidence** that these trends are attributable to human influences” (pp. 240-241)

The absence of detectable US-wide trends in flooding is consistent with the findings in the previous section of absence of coherent changes in extreme precipitation.

## 7.8 Droughts

Assessments of drought trends were as follows.

AR6: “**Few** AR6 regions show observed increases in meteorological drought” (Section 11.9, p. 1575),

AR6: “**Increasing trends in agricultural and ecological droughts have been observed on all continents** (*medium confidence*), but decreases only in one AR6 region (*medium confidence*). Increasing trends in hydrological droughts have been observed in a few AR6 regions.” (Chapter 11 Summary)

NCA17: “As a consequence of this increased precipitation, **drought statistics over the entire CONUS have declined.**” (p. 233)

NCA17: “Recent droughts and associated heat waves have reached record intensity in some regions of the United States; however, by geographical scale and duration, the Dust Bowl era of the **1930s remains the benchmark** drought and extreme heat event in the historical record (very high confidence).” (p.231)

SREX: “From a paleoclimate perspective, **recent droughts are not unprecedented**, with severe ‘megadroughts’ reported in the paleoclimatic record for Europe, North America, and Australia.” (p. 170)

As shown in ~~Figure 7.8.1~~ Figure 6.8.1, US long term data shows an insignificantly declining ~~tendency~~ trend toward extreme dryness (-0.001% per year)

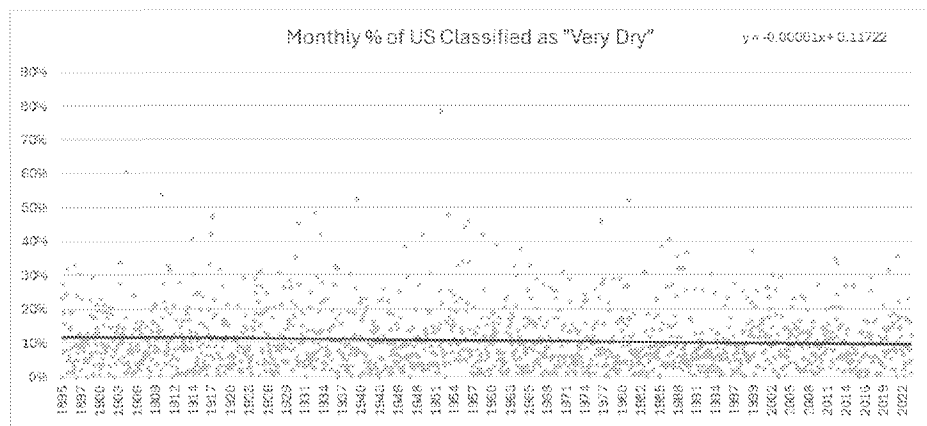


Figure 7-Figure 6.8.1: US dryness (%) 1895–2023. Source: NOAA [ [HYPERLINK "https://www.ncei.noaa.gov/access/monitoring/uspa/wet-dry/0"](https://www.ncei.noaa.gov/access/monitoring/uspa/wet-dry/0) ]

Kogan et al. (2020) examines a 38-year high-resolution satellite-based drought measure and concludes that global drought has not intensified and is not connected to climate change: “it is possible to state firmly that global and main grain countries’ drought area and intensity trends have not been following global climate warmings since 1980’s.”

## 6.9 Wildfires

The IPCC has not provided an assessment of wildfires. As shown in Figure 7-Figure 6.9.1, global wildfire activity as measured by European Space Agency shows a downward trend in the 21<sup>st</sup> century.

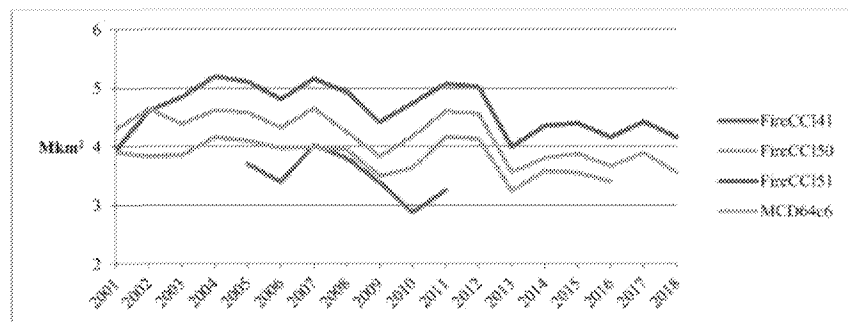


Figure 7-Figure 6.9.1: Global wildfire area 2001-2018. Source: Copied from Lizundia-Loiola et al. (2021). Note: the different coloured lines represent different data products derived from based on different satellites and algorithms used

**Commented [A8]:** I thought the trends were due to declining fires in the Amazon, masking any climate-related trend?

**Commented [A9R8]:** “global area burned appears to have overall declined over past decades, and there is increasing evidence that there is less fire in the global landscape today than centuries ago.” Doerr and Santin, Proc Royal Society 2016

**Commented [SK10R8]:** but see [ [HYPERLINK "https://www.science.org/doi/10.1126/science.aal4108"](https://www.science.org/doi/10.1126/science.aal4108) ] where they attribute the decline to changes in Ag practices.

US data from the National Interagency Fire Centre (NIFC) from 1926 to 2023 are shown in Figure 8.9.2.

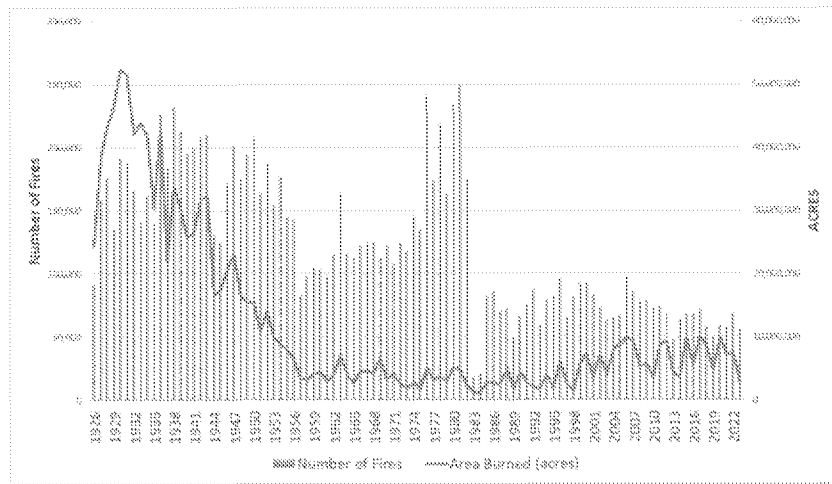


Figure 8.9.2: US wildfires 1926 to 2023. Source: Post-2018: National InterAgency Fire Centre data  
Pre-2017 wearchive.org

Note that the NIFC has removed the pre-1960 data from its current website. They claim it is because measurement methods changed after 1960. This explanation seems inadequate since agencies blend temperature and extreme weather data series in other contexts when measurement systems changed. The measurement of wildfires has improved since the early 20<sup>th</sup> century, so any bias will be towards understating early wildfire counts. Nonetheless just focusing on the post-1985 interval the number of fires is not increasing. The area burned did increase but only until about 2007.

Forest fires have always been a part of nature, and they can certainly create conditions that are inhospitable in the short term for all life including humans. Science has confirmed the overall benefit and necessity of the occurrence of forest fires. While recent high-profile fires and seasons serve as a reminder of the potential destructive impact, the highest profile forest fire remains the 1910 Big Blowup fire which destroyed over three million acres including the elimination of entire towns like Taft, MT (Apple 2020). The 1910 fire reshaped the U.S. Forest Service (National Forest Foundation 2022) leading to a focus on fire suppression with a primary goal to defeat all forest fires (Forest History Society 2022). This led to the 10 am rule in 1935 that meant requiring that all fires spotted on any day had to be controlled by 10 am the following day at 10 am (National Forest Foundation 2022).

While defeating all fires is seemed certainly a noble goal, questions began to arise as to whether this behavior "followed the science" (US Forest Service 2022). Over time the U.S. Forest Service has begun to rethink its behavior goals, recognizing that new approaches such as prescribed burns, fuel

elimination, and controlled wildfires are more appropriate (Sommer 2016). Recent research is validating this approach and recognizing that more frequent smaller fires in forests likely result in the most healthy/healthier forests, water ecosystems and biodiversity (Stephens et al. 2021).

Active fire suppression since 1900 makes it difficult to establish a natural baseline for wildfire activity in the US because of active fire suppression activity since 1900. However, paleoclimatic evidence indicates, however, that past wildfire activity was much higher than at present today. Marlon et al. (2012) used sedimentary charcoal layers to reconstruct fire history of western US for the past 1400 years. They also and also fit a model to predict expected fire activity as a function of climatic conditions. Their results are summarized in Figure 7 Figure 6.9.3 below (from Figure 2 in their paper).

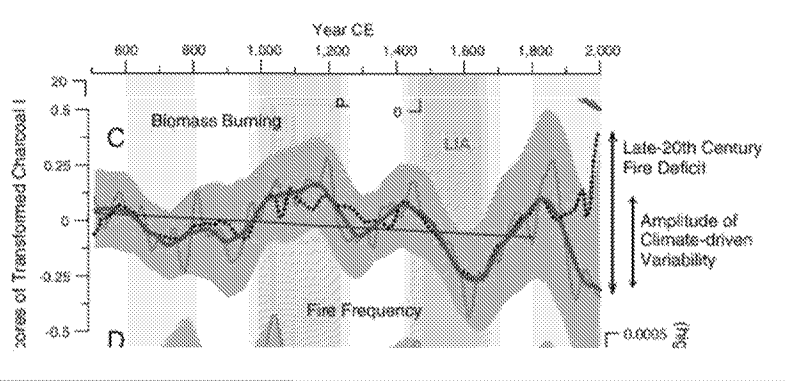


Figure 7. Figure 6.9.3 Fire frequency and fire deficit in the US. In their figure, the red line shows the smoothed charcoal record and the black dotted line shows the predicted charcoal record based on climatic conditions. Source: Copied from Marlon et al. (2012)

In their figure, the red line shows the smoothed charcoal record and the black dotted line shows the predicted charcoal record based on the statistical model. The gap at the end implies there has been a growing wildfire deficit over the 20<sup>th</sup> century. In other words, however much fire was observed in the 20<sup>th</sup> century, it was less than what would have been observed in previous centuries based on the climatic conditions. Parks et al. (2025) likewise find that despite the recent increase in wildfire burn area in North America, a significant wildfire deficit remains relative to historical wildfire regimes.

#### 7.10 Summary

Contrary to popular belief and frequent claims by the media and many political leaders, there are no statistically significant climatological trends most types of extreme weather exhibit no statistically significant trends, nor do assessment reports of the IPCC or the NCA claim to have detected any. There has been an increase in hot days in the US since the 1950s, a point emphasized by the IPCC AR6, but a decrease relative to the 1920s and 1930s. Extreme convective storms, hurricanes, tornadoes, floods and droughts exhibit considerable natural variability but long-term trends are not detectable. Some increases in extreme precipitation events can be detected in some regions over short intervals but there are no long-term trends over long periods and at the regional scale, the trends do not persist. Wildfire activity has increased in the US in recent decades but has declined globally, and in the US is

wildfire incidence is significantly low down significantly relative to the early 20<sup>th</sup> century and to the estimated natural baseline level. Changes in US wildfire activity are strongly affected by changing forest fire management practices.

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*(RM May 13 edits: Inserted Judy's new Sec 8.3 + wildfire text, John's revised Fig 8.4.2 short text in place of Table 8.2.1.)*

*(IRC edits May 14: folded the results from the three precipitation extremes from Ross's analysis into each of the already-discussed sections, minor edits)*

*(IC light edits May 14)*

## **78 Extreme weather in the US and elsewhere**

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### **78.1 Introduction**

High impact weather extremes, usually related to temperature, and/or precipitation, and/or excessive wind, often can disrupt infrastructure and therefore endanger human health and thriveability/wellbeing. Indeed, the ability of any surface-dwelling species to live productively is somewhat constrained by these extremes which in essence create the bounding limits for survival. The issue is not whether extremes occur, for they are intrinsic to the chaotic climate system. Rather, it is whether there are long-term (decadal scale) changes in the frequency and/or character of extremes ("detection"), as well as the extent to which such changes here is whether these extremes, and their attendant changes in potential danger hazards, may be changing and if so whether the change is in response caused by anthropogenic emissions increases in infrared-absorbing of greenhouse gases (GHGs) ("attribution"). (e.g., IPCC AR6 Seneviratne et al. 2021).

It is naïve to assume that any recent unprecedented extreme event observed recently is caused by human influences on the climate. Unfortunately, that's that assumption is wrong in two ways. First, climate is about the statistical properties of weather over decades, not single events. And second, there are only about 130 years of the reliable. Unfortunately, observational records that can be analyzed statistically extend back only for the sample of time from which we are able to quantitatively analyze variations in extreme events is quite brief, about around 130 years. That brief interval does not. This period certainly does not begin to contain all of the extreme events that the climate system is able to create naturally on its own. Over geologic time the climate system has generated an (essentially) infinite variety of weather patterns and extremes which that humans have never observed, and thus do not enter our are absent from the databases from which used to determine extreme statistics. are determine d. [see *Perils of short data records* below]. Thus, assuming that a for that reason, attributing climate pattern or an extreme event hitherto unprecedented in the record not experienced in our lifetime must therefore be the result of enhanced GHG concentrations requires the assumptions about the smallness/magnitude of that natural variations, are insignificant.

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This is especially true for precipitation events. The hydrological literature has long noted the phenomenon of *Long-Term Persistence* (LTP) in rainfall data (Hurst 1951, Cohn and Lins 2005, Markonis and Koutsoyiannis 2015). LTP has a formal mathematical definition but it can be thought of intuitively as the presence of natural variations with strong autocorrelation properties that result in cycle-like behavior on long time scales. The presence of LTP requires very long data samples/records to obtain accurately accurate estimates of variance/variability. Analysis of, analysis of data samples that are records short relative to the LTP scale will tend to yield underestimate variability, therefore underestimated variances which in turn yields overstating the significance of apparent trends and underestimation underestimating of the likelihood of extreme events (Cohn and Lins 2005).

<sup>1</sup> For example, under the simplest statistical assumptions there is a 37 percent chance that a 100-year event is NOT present in a century-long record.

A good example of LTP is the eight-century long record of the annual minimum height of the Nile River observed at Roda Island in Cairo (shown below) in Figure B7.1.1. Since human influences on the global climate were negligible before the 20<sup>th</sup> century, the century-scale variability of the thirty-year average is entirely natural; Egyptians of the seventh and eight centuries would have been incorrect to assume that the worsening drought during that time was the “new normal.”

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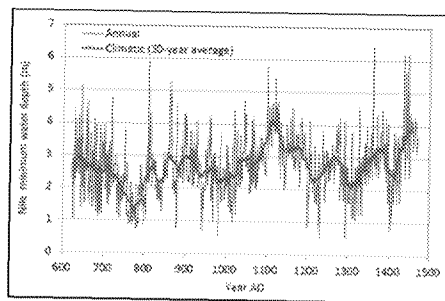


Figure B7.1.1: Nile River discharge [details, source]

With these caveats in mind, we examine the evidence for changes in selected weather and climate extremes. A theme that emerges when reviewing this topic is the wide gap between public perceptions and scientific evidence. It has become routine in media discussions, government and private sector discussions and even in some academic literature to make generalized assertions that extreme weather of all types is getting worse due to GHGs and climate change. Yet expert assessments have not typically drawn such sweeping conclusions and instead have emphasized the difficulty both of identifying specific trends and establishing a causal connection with anthropogenic forcing.

In the sections to follow we cite provide excerpts from various IPCC and NCA assessment reports denoting the sources as follows:

For the benefit of readers who may not have read the relevant reports in the Appendix to this chapter we will begin provide with extended excerpts of these findings from previous IPCC and NCA assessments, then in the remainder of this chapter survey additional data relevant to US and global extreme weather trends.

## 8.2 Review of IPCC and NCA Findings on Extreme Weather

The sources we review will be denoted as follows:

SREX: The IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (2012)

AR5: The IPCC Fifth Assessment Report Working Group 1 (2013)

AR6: The IPCC Sixth Assessment Report Working Group 1 (2021)

NCA17: The US Climate Science Special Report of the Fourth National Climate Assessment (2017) Volume I Chapter 6.

Note that in the excerpts, provided *italics* are in the original whereas boldface emphasis is added.

### 8.2.1 Overview Context: IPCC Assessment of signal emergence in extreme weather types (AR6 WG1 Table 12.12)

This chapter is concerned with detection of trends. Chapter 7 looked at attribution including for extreme weather. Since there is considerable public interest in the question of whether humans are causing trends in extreme weather to get worse it is useful to begin with the summary Table 8.2.1 which reproduces the findings of AR6 Table 12.12 which indicates, for 24 major weather event and impact types, whether a signal of anthropogenic forcing has been detected in the historical record (column 1), whether such a signal is likely to emerge by 2050 under the extreme RCP8.5 scenario (column 2) and whether it is likely to emerge by 2100 under RCP8.5 forcing (column 3). It should be borne in mind that the latter two columns suffer from the deficiencies of GCMs discussed in Chapter XX. And as we discussed in Ch. X7 on attribution, AR6 offers conflicting messages about attribution of extreme weather. Nevertheless, we provide this Table for reference context:

Several patterns stand out. First, detection of an anthropogenic signal is asserted with *high confidence* in only four of the 24 weather impact categories, and with *medium confidence* in a further four. The IPCC does NOT claim to have detected an anthropogenic signal in the remaining 16 categories. Of the four *high confidence* assertions, two are for changes in average temperatures (air and ocean), which are not measures of extreme weather. Further, two of the four *medium confidence* assertions are related to ocean chemistry and are also not related to extreme weather. The IPCC does NOT assert a detectable human influence on many non-temperature weather features such as wind, precipitation, flooding, and droughts.

Second, columns 2 and 3 show that the IPCC expects very few anthropogenic trends to emerge within this century, even under the most extreme forcing scenario. As we discuss in Section 1.2 the RCP8.5 scenario is an implausible high-end storyline, not a "base case" or "business-as-usual" projection. Even so, most weather impacts are not expected to show an anthropogenic signal this century. Natural variability dominates patterns of extreme weather systems and simplistic assertions of trend detection are frequently undermined by regional heterogeneity and trend reversals over time.

| Climate Impact Driver Type | Climate Impact Driver Category      | Already Evident in the Historical Record? | Emerging by 2050 in Most Extreme CO <sub>2</sub> Emissions Scenario? | Emerging by 2100 in Most Extreme CO <sub>2</sub> Emissions Scenario? |
|----------------------------|-------------------------------------|-------------------------------------------|----------------------------------------------------------------------|----------------------------------------------------------------------|
| Heat & Cold                | Average air temperature             | YES in most regions                       | YES                                                                  | YES                                                                  |
|                            | More heat extremes                  | YES in most regions                       | YES in most regions                                                  | YES                                                                  |
|                            | Fewer cold extremes                 | YES in a few regions                      | YES in most regions                                                  | YES                                                                  |
|                            | Less frost                          | NO                                        | NO                                                                   | NO                                                                   |
| Wat & Dry                  | Average Rain (Increase or Decrease) | NO                                        | YES (in up. YES (decr.)                                              | YES (in up. YES (decr.)                                              |
|                            | River Flooding                      | NO                                        | NO                                                                   | NO                                                                   |
|                            | Heavy precip. & elevated flood      | NO                                        | NO                                                                   | YES in a few regions                                                 |
|                            | Landslide                           | NO                                        | NO                                                                   | NO                                                                   |
|                            | Aridity                             | NO                                        | NO                                                                   | NO                                                                   |
|                            | Hydrologic Drought                  | NO                                        | NO                                                                   | NO                                                                   |
|                            | Agricultural & ecological drought   | NO                                        | NO                                                                   | NO                                                                   |
|                            | Fire weather                        | NO                                        | NO                                                                   | NO                                                                   |
| Wind                       | Average wind speed                  | NO                                        | NO                                                                   | NO                                                                   |

|              |                                  |                          |                      |                 |
|--------------|----------------------------------|--------------------------|----------------------|-----------------|
|              | Severe wind storms               | NO                       | NO                   | NO              |
|              | Tropical cyclones                | NO                       | NO                   | NO              |
|              | Sand and dust storms             | NO                       | NO                   | NO              |
| Snow and ice | Snow, glacier & ice sheet        | NO                       | YES in a few regions | YES Arctic snow |
|              | Permafrost                       | YES                      | YES                  | YES             |
|              | Lake & river ice                 | NO                       | YES                  | YES             |
|              | Arctic sea ice                   | YES                      | YES                  | YES             |
|              | Antarctic sea ice                | NO                       | YES                  | YES             |
|              | Higher snowfall and ice storm    | NO                       | NO                   | NO              |
|              | Heat                             | NO                       | NO                   | NO              |
|              | Snow melt/retreat                | NO                       | NO                   | NO              |
|              | Perpetual snowfield              | NO                       | YES                  | YES             |
| Coastal      | Coastal flood                    | NO                       | NO                   | NO              |
|              | Coastal erosion                  | NO                       | NO                   | NO              |
|              | Average ocean temperature        | YES                      | YES                  | YES             |
| Other Ocean  | Major heat wave                  | NO                       | NO                   | NO              |
|              | Ocean acidity                    | NO                       | YES                  | YES             |
|              | Ocean salinity                   | YES                      | YES                  | YES             |
|              | Dissolved oxygen                 | YES (Pacific & S. Ocean) | YES                  | YES             |
| Other        | Air pollution/smog               | NO                       | NO                   | NO              |
|              | Solar or IR radiation at surface | NO                       | NO                   | NO              |

Table 8.2.1: IPCC AR6 summary of the probable emergence of an anthropogenic signal above natural climate variability for all global or regional “climate impact drivers” (CIDs) of concern for humans and ecosystems in response to increasing atmospheric greenhouse gas concentrations (primarily CO<sub>2</sub>). Source: Table adapted from report of Working Group I, Table 12.12). Red = high confidence; yellow = medium confidence; green = no anthropogenic signal detectable above natural variability (50% confidence).

Taking wind as an example, the IPCC claims that an anthropogenic signal has NOT yet emerged in average wind speeds, severe wind storms, tropical cyclones, or sand and dust storms, and none are expected to emerge this century even under an extreme emissions scenario. The same applies to drought and fire weather. This table alone suffices to illustrate the gap between IPCC expert assessments of extreme weather and discussions in the popular media and political arenas. As we show below, the Table reflects longstanding conclusions of the IPCC and other assessment bodies. In the next few sections we will simply present without comment excerpts from past assessment reports.<sup>2</sup> In selecting these excerpts, we’ve focused on the highest-level summaries to avoid accusations of bias through “cherry-picking.”

## B7.2 Context: detection is not attribution

This chapter is concerned with detection of trends. Chapter 29 looked at causal attribution, with Section 29.4 specifically addressing extreme weather. If no trend is detected, then clearly there is no basis for attribution. But even where a trend is observed attribution should not be assumed automatically to follow. Since there is considerable public interest in the question of whether humans are causing trends in extreme weather to get worse, it is useful to recall that AR6 Table 12.12 indicates that, for 34 major weather event and impact types, detection of an anthropogenic signal is

<sup>2</sup>In these excerpts we have added bold face emphasis while italicized emphasis on confidence terms appears in the original sources. Citations in quoted text can be found in the underlying reports but are not reproduced here.

asserted with *high confidence* in only four of the 34 weather impact categories, - and with *medium confidence* in a further four. The IPCC does not claim to have detected an anthropogenic signal in the remaining 26 categories. Of the four *high confidence* assertions, two are for changes in average temperatures (air and ocean), which are not measures of extreme weather. Also, two of the four *medium confidence* assertions are related to ocean chemistry and are also not related to extreme weather. The IPCC does not assert a detectable human influence on many non-temperature weather features such as wind, precipitation, flooding, and drought.

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### 87.2.73 Hurricanes and Tropical Cyclones

The AR6 assessment provides the following assessment of tropical cyclones (TCs; used here to be synonymous with hurricanes):

AR6: There is *low confidence* in most reported long-term (multidecadal to centennial) trends in TC frequency or intensity-based metrics due to changes in the technology used to collect the best-track data. (IPCC, 2021)

AR6: It is *likely* that the global proportion of major (Category 3–5) tropical cyclone occurrence has increased over the last four decades. . . . There is *low confidence* in long-term (multi-decadal to centennial) trends in the frequency of all-category tropical cyclones. (IPCC, 2021)

AR6: A subset of the best-track data corresponding to hurricanes that have directly impacted the United States since 1900 is considered to be reliable, and shows *no trend* in the frequency of U.S. landfall events. (IPCC, 2021)

Since 1980, when satellite observations fully covered the global oceans, we have confidence in the numbers of total global hurricanes and major hurricanes (Category 3 and higher). Figure 87.3.1 shows that on average, each year there are about 50 hurricanes, with about 25 reaching major hurricane status (RN Maue, 2025). Substantial year-to-year and decadal variability is seen; over the time period, there is a slight decreasing trend in the number of hurricanes and a slight but insignificant increasing trend in the number of major hurricanes. From these two trends, it is inferred that there is an overall trend of increasing percentage of major hurricanes, relative to the total number of hurricanes.

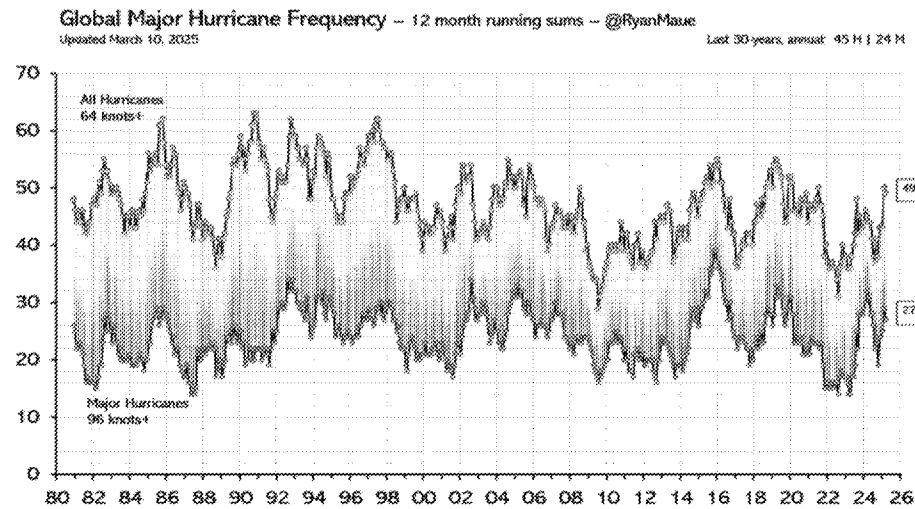


Figure 87.3.1: Global frequency of hurricanes and major hurricanes since 1980.

Global hurricane statistics are dominated by the Northwest Pacific Ocean which accounts for ~35 percent of total global hurricanes whereas the Atlantic accounts for ~15% percent of global

hurricanes (CSU, 2025). Data in the Atlantic Ocean extends further back than in the other ocean basins, and is most relevant to U.S. policy makers.

Figure 7.3.2 shows the frequency of Atlantic hurricanes (HR) and major hurricanes (MHR, Category 3 and higher) back to 1920. Data prior to 1965 (the onset of satellite observations in the Atlantic, shaded in blue) shows some undercounting, with data prior to 1920 showing substantial undercounting (GA Vecchi and TR Knutson, 2011). All measures of Atlantic hurricane activity show a significant increase since 1970. However, the period from 1971-1994 was a period of exceptionally low activity, with high values of hurricane activity (comparable to the past two decades, even with undercounting) also observed during the 1950's and 1960's, and also even in the 1930's.

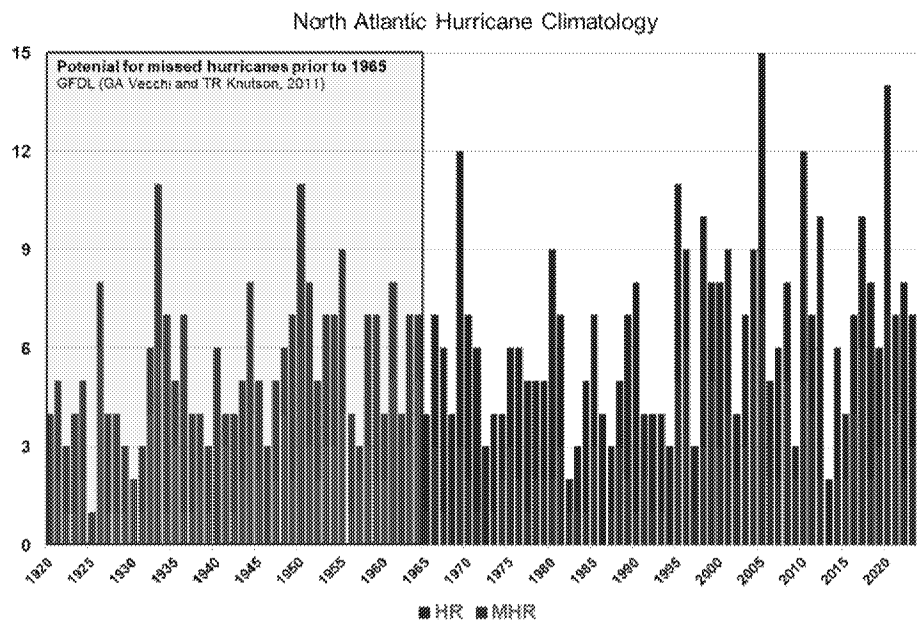


Figure 7.3.2: Atlantic frequency of hurricanes and major hurricanes since 1920. Source (NHC, 2024)

It is seen from Figure 7.3.2 that Atlantic hurricanes show strong variations on decadal and multi-decadal time scales in the observed record. These variations are associated primarily with the Atlantic Multidecadal Oscillation (AMO), which is associated with basin-wide sea surface temperature and sea level pressure fluctuations associated with large scale ocean circulation patterns. The AMO was in its warm phase during 1926-1970 and 1995-present; the AMO was in its cool phase during 1971-1994. The greatest impact of the AMO is on the number of major hurricanes (Category 3+). The relationship of the AMO to major hurricane activity in the Atlantic was identified by Goldenberger et al. (2001) to be associated with above normal SSTs and decreased vertical shear associated with the warm AMO (see also GD-Bell and M-Chelliah, 2006; PI-Klotzbach et al., 2018).



Klotzbach et al. (2018) conducted a comprehensive evaluation of the landfalling hurricane data for the Continental U.S. since 1900. Figure 8.7.3.3 updates the Klotzbach et al. analysis through 2024. While the largest numbers of hurricanes are from 2004, 2005 and 2020, the overall trend since 1920 is not statistically significant from zero. Figure 8.7.3.3 also shows the time series for major hurricane landfalls (Category 3-5). The largest year in the record is 2005, with 4 major hurricane landfalls. However, during the period 2006 through 2016, there were no major hurricanes striking the U.S., which is the longest such period in the record since 1920.

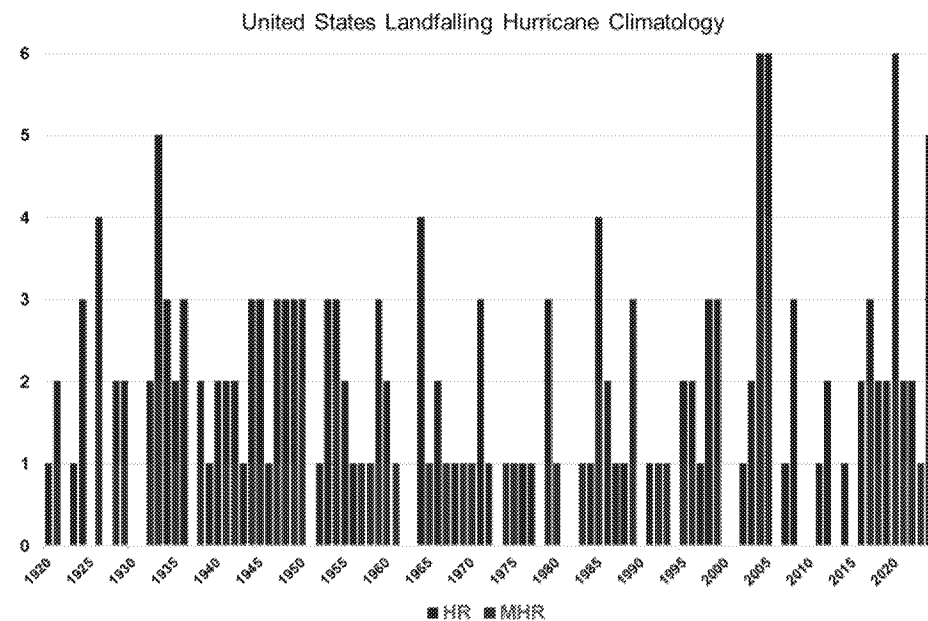


Figure 8.7.3.3: US landfalling frequency of hurricanes and major hurricanes since 1920. Source (NOAA HRD(G), 2024)

Substantial interannual to multidecadal variability in U.S. landfall activity is seen Figure 7.3.3. In Klotzbach et al. (2018) examined how the landfall counts vary with ENSO (El Niño versus La Niña) and the warm versus cold phases of the Atlantic Multidecadal Oscillation (AMO).

Villarini et al. (2012) provide an analysis of U.S. hurricane landfalls back to 1878. While it is possible that some landfalls were missed in the late 19<sup>th</sup> century owing to sparsely populated regions on the Gulf Coast, it is remarkable that the highest year in the entire record, with 7 landfalls, is 1886.

Table 8.7.3.1 shows the 10 strongest hurricanes (plus ties) to make U.S. landfall. Of the hurricanes that have made landfall with sustained winds greater than 150 mph, only one has occurred in the busy period since 2004 the 21<sup>st</sup> century.

**Table 8.7.3.1** Strongest hurricanes to make landfall along the US coast. Source (NOAA HRD(b), 2024)

| Rank | Year | Landfall Wind (MPH) | Name          |
|------|------|---------------------|---------------|
| 1    | 1935 | 185                 | "Labor Day"   |
| 2    | 1969 | 175                 | Camille       |
| 3    | 1992 | 165                 | Andrew        |
| 4    | 2018 | 160                 | Michael       |
| 5    | 1856 | 150                 | "Last Island" |
| 5    | 1886 | 150                 | "Indianola"   |
| 5    | 1919 | 150                 | -----         |
| 5    | 1932 | 150                 | "Freeport"    |
| 5    | 2004 | 150                 | Charley       |
| 5    | 2020 | 150                 | Laura         |
| 5    | 2021 | 150                 | Ida           |
| 5    | 2022 | 150                 | Ian           |

While an increase in hurricane intensity has long been hypothesized to occur as global sea surface temperatures increase, identification of any significant trend in the hurricane data is hampered by a short data record and substantial natural variability.

In summary, analyses of both global and regional variability and trends of hurricane activity provide the basis for detecting changes and understanding their causes. The relatively short historical record of hurricane activity, and the even shorter record from the satellite era, is not sufficient to assess whether recent hurricane activity is unusual relative to the background natural variability. Atlantic hurricane processes are influenced substantially by the natural modes of ocean circulation variability in the Atlantic, notably the Atlantic Multidecadal Oscillation. The AR6 assessed this topic as follows:

AR6: There is low confidence in most reported long-term (multidecadal to centennial) trends in TC frequency or intensity-based metrics due to changes in the technology used to collect the best-track data. (Chapter 1.1, p. 1585)

AR6: It is likely that the global proportion of major (Category 3–5) tropical cyclone occurrence has increased over the last four decades. There is low confidence in long-term (multi-decadal to centennial) trends in the frequency of all-category tropical cyclones. (SPM A.3.4)

AR6: A subset of the best-track data corresponding to hurricanes that have directly impacted the United States since 1900 is considered to be reliable, and shows no trend in the frequency of U.S. landfall events. (Chapter 1.1 Summary, p. 1585)

Hurricane strength records for the North Atlantic and the Western Pacific go back to 1950 and the record does not show an increase in either total or major TCs. Figure 8.3.1 was published by Roger Pielke Jr. as an update to the Best Track data series originally presented in Weinkle et al. (2012).

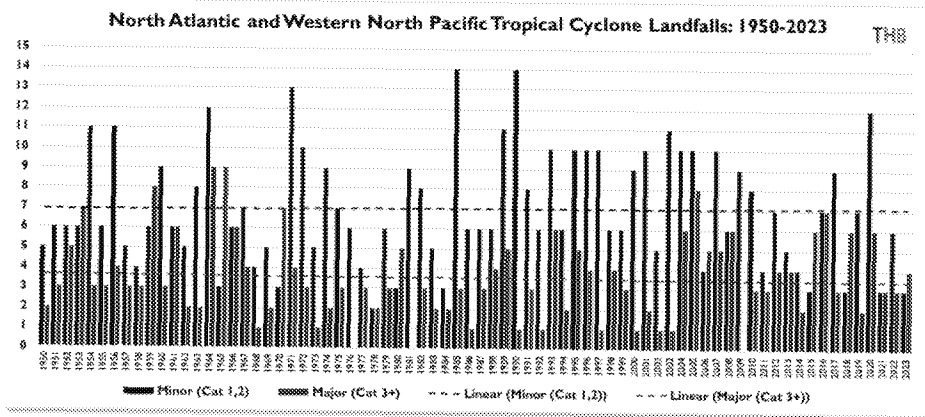


Figure 8.3.1: Tropical Cyclone Landfalls. Source: [HYPERLINK "https://rogerpielkejr.substack.com/p/global-tropical-cyclones"], Weinkle et al. (2012)

Similarly, Figure 8.3.2 (Maue 2025, [HYPERLINK "https://climatlas.com/tropical/"]) shows that both all hurricanes and major hurricanes have not become more common since 1980, the period of rapidly growing human influences. In fact, both numbers have trended down slightly since the 1990s.

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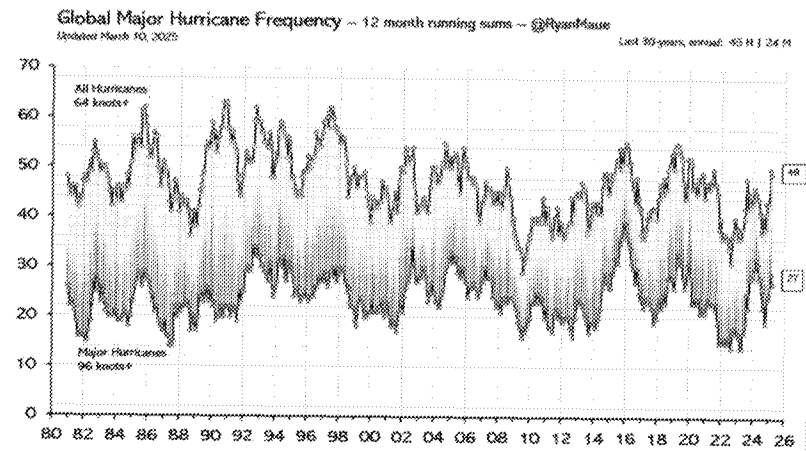


Figure 8.3.2: Global hurricane frequency. Source: Maue (2025)

A metric that combines the number, duration, and strength of TCs is the Accumulated Cyclone Energy (ACE) index maintained at Colorado State University, shown in Figure 8.3.3. It clearly shows no long-term increase, in fact declining slightly since 1990.

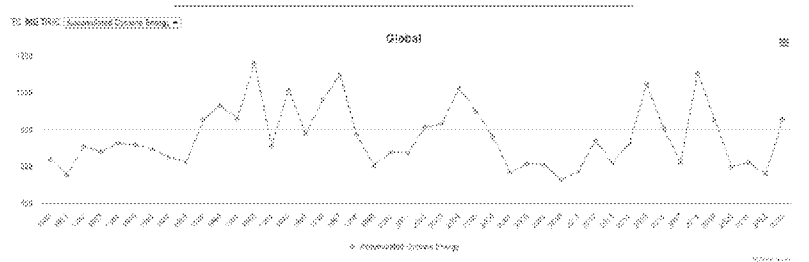


Figure 8.3.3: Global Accumulated Cyclone Energy. Source: Klotzbach (2025)

[HYPERLINK "<https://tropical.atmos.colostate.edu/Realtime/index.php?arch&loc=global>"]

Note that Tu et al. (2024) report that the Power Dissipation Index (PDI), another different measure that combines hurricane number, duration, and strength, has either remained unchanged or has declined in all global oceanic basins since the mid-1990s.

Today's global climate simulations are too coarse to project changes in TCs directly. Rather, projections are derived from finer "downscaled" simulations or proxies involving sea surface temperatures, winds, and aerosols. By those methods, a warming climate is expected to show declining hurricane formation rates (Chang et al. 2022). Climate models also project fewer Tropical Cyclones under future global warming, and even though models project they will increase in strength, the annual averages of rainfall maxima decline (Stancfield et al. 2020).

#### 8.3 Tornadoes SREX (p. 159):

There have been no significant trends observed in global tropical cyclone frequency records, including over the present 40-year period of satellite observations (e.g. Webster et al., 2005). Regional trends in tropical cyclone frequency have been identified in the North Atlantic, but the fidelity of these trends is debated (Holland and Webster, 2007; Landsea, 2007; Mann et al., 2007a). Different methods for estimating undercounts in the earlier part of the North Atlantic tropical cyclone record provide mixed conclusions (Chang and Guo, 2007; Mann et al., 2007b; Kunkel et al., 2008; Vecchi and Knutson, 2008). Regional trends have not been detected in other oceans (Chan and Xu, 2009; Kubota and Chan, 2009; Callaghan and Power, 2011). It thus remains uncertain whether any observed increases in tropical cyclone frequency on time scales longer than about 40 years are robust after accounting for past changes in observing capabilities (Knutson et al., 2010).

#### AR5 (pp. 216-17):

Current data sets indicate no significant observed trends in global tropical cyclone frequency over the past century and it remains uncertain whether any reported long-term increases in tropical cyclone frequency are robust, after accounting for past changes in observing capabilities (Knutson et al., 2010). No robust trends in annual numbers of tropical storms, hurricanes and major hurricanes counts have been identified over the past 100 years in the North Atlantic basin. Measures of land-falling tropical cyclone frequency

(Figure 2.34) are generally considered to be more reliable than counts of all storms which tend to be strongly influenced by those that are weak and/or short lived. Callaghan and Power (2011) find a statistically significant decrease in Eastern Australia land-falling tropical cyclones since the late 19th century although including 2010/2011 season data this trend becomes non-significant (i.e. a trend of zero lies just inside the 90% confidence interval). Significant trends are not found in other oceans on shorter time scales (Chan and Xu, 2009; Kubota and Chan, 2009; Mohapatra et al., 2011; Weinkle et al., 2012), although Grinstead et al. (2012) find a significant positive trend in eastern USA using tide gauge data from 1923–2008 as a proxy for storm surges associated with land-falling hurricanes. Differences between tropical cyclone studies highlight the challenges that still lie ahead in assessing long-term trends.

In summary, this assessment does not revise the SREX conclusion of *low confidence* that any reported long-term (centennial) increases in tropical cyclone activity are robust after accounting for past changes in observing capabilities. More recent assessments indicate that it is *unlikely* that annual numbers of tropical storms, hurricanes and major hurricanes counts have increased over the past 100 years in the North Atlantic basin. Evidence, however, is for a virtually certain increase in the frequency and intensity of the strongest tropical cyclones since the 1970s in that region.

AR6 (p. 1585)

There is *low confidence* in most reported long-term (multidecadal to centennial) trends in TC frequency or intensity-based metrics due to changes in the technology used to collect the best-track data. This should not be interpreted as implying that no physical (real) trends exist, but rather as indicating that either the quality or the temporal length of the data is not adequate to provide robust trend detection statements, particularly in the presence of multidecadal variability.

There are previous and ongoing efforts to homogenize the best-track data (Elner et al., 2009; Kossin et al., 2013, 2020; Choy et al., 2015; Landsea, 2015; Emanuel et al., 2018) and there is substantial literature that finds positive trends in intensity-related metrics in the best-track during the “satellite period”, which is generally limited to the past ~40 years (Kang and Elner, 2012; Kishitani et al., 2012; Kossin et al., 2013, 2020; Mei and Xie, 2016; Zhao et al., 2018; Tawale and Tsuboki, 2019). When best-track trends are tested using homogenized data, the intensity trends generally remain positive, but are smaller in amplitude (Kossin et al., 2013; Holland and Bruyère, 2014). Kossin et al. (2020) extended the homogenized TC intensity record to the period 1979–2017 and identified significant global increases in major TC exceedance probability of about 6% per decade.<sup>2</sup> In addition to trends in TC intensity, there is evidence that TC intensification rates and the

<sup>2</sup>The underlined text referenced a study (Kossin et al., 2020) that later retracted a portion of its findings. Those authors assembled a dataset on global TC intensity spanning 1979 to 2017 from which they claimed that the global fraction of TCs reaching major status (Cat 3–5) rose from 27% during 1979–1997 to 31% during 1998–2017 and that the increase was statistically significant. However, closer examination of their results showed a significant increase only in the North Atlantic (15% to 24%) whereas changes in all other basins (Eastern Pacific, Western Pacific, North Indian, South Indian, South Pacific) were not statistically significant in a subsequent correction ([HYPERLINK "<https://www.pnas.org/doi/10.1073/pnas.2021573117>"]]). Kossin et al. stated that the global probability of observing a major TC rose from 24% during 1979–1997 to 27% in the same period and that the evidence for statistical significance was now weaker. Nevertheless, the authors claimed that the correction did not affect their conclusions.

frequency of rapid intensification events have increased within the satellite era (Goshtawal et al., 2012; Balaguru et al., 2018; Bhatia et al., 2018). The increase in intensification rates is found in the best-track as well as the homogenized intensity data.

**A subset of the best-track data corresponding to hurricanes that have directly impacted the United States since 1900 is considered to be reliable, and shows no trend in the frequency of U.S. landfall events (Knutson et al., 2019).**

AR6: "[O]bservational trends in tornadoes, hail, and lightning associated with severe convective storms are not robustly detected due to insufficient coverage of the long-term observations. There is *medium confidence* that the mean annual number of tornadoes in the USA has remained relatively constant." (Chapter 11, section 11.7.3, p. 1594)

As noted there is no evidence of trend in US tornadoes or extreme convective storms. Extreme precipitation will be discussed further below.

#### 8.7.34 Temperature extremes

The AR6 assessment focused on the period after 1950 and reported increasing trends in heatwave frequency and intensity. The NCA17 however noted that heatwave activity in the US reached a peak in the 1930s.

AR6: "It is *virtually certain* that hot extremes (including heatwaves) have become more frequent and more intense across most land regions since the 1950s, while cold extremes (including cold waves) have become less frequent and less severe" (SPM, A3.1)

AR6: "In North America, there is very robust evidence for a *very likely* increase in the intensity and frequency of hot extremes and decrease in the intensity and frequency of cold extremes for the whole continent, though there are substantial spatial and seasonal variations in the trends. Minimum temperatures display warming consistently across the continent, while there are more contrasting trends in the annual maximum daily temperatures in parts of the USA." (Chapter 11, p. 1556)

NCA17: "Changes in warm extremes are more nuanced than changes in cold extremes. For instance, the warmest daily temperature of the year increased in some parts of the West over the past century, but there were decreases in almost all locations east of the Rocky Mountains. In fact, all eastern regions experienced a net decrease, most notably the Midwest (about 2.2°F [1.2°C]) and the Southeast (roughly 1.5°F [0.8°C])." (pp. 190-191)

NCA17: "Since the mid-1960s, there has been only a very slight increase in the warmest daily temperature of the year (amidst large interannual variability). Heat waves (6-day periods with a maximum temperature above the 90th percentile for 1961–1990) increased in frequency until the mid-1930s, became considerably less common through the mid-1960s, and increased in frequency again thereafter. As with warm daily temperatures, heat wave magnitude reached a maximum in the 1930s." (pp. 190-191)

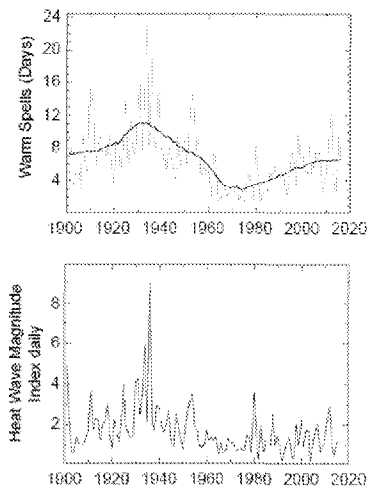


Figure 8.7.34.1: US Heat waves since 1900. Source: NCA17 Figure 6.4

#### 8.7.34.1 Temperatures in the US are becoming less extreme

Daily maximum temperatures in the warm season (TMax, May-Sep) and daily minimum temperatures in the cold season (TMin, Dec-Mar) are available beginning in Dec. 1898 (126 years). The dataset consists of 1,211 CONUS stations designated as United States Historical Climate Network or USHCN stations (see Figure 8.7.34.12; Quinlan et al. 1997, Karl et al. 1999). These stations were selected by NOAA as having the fewest problematic issues with gaps, station moves and instrument changes. Where gaps still exist, nearby stations (bias-corrected) were merged so that the median volume of data available for a station is 98%. Although there are certainly errors in the dataset, with over 1,000 stations we can have relatively high confidence in any underlying signal that might be discovered.

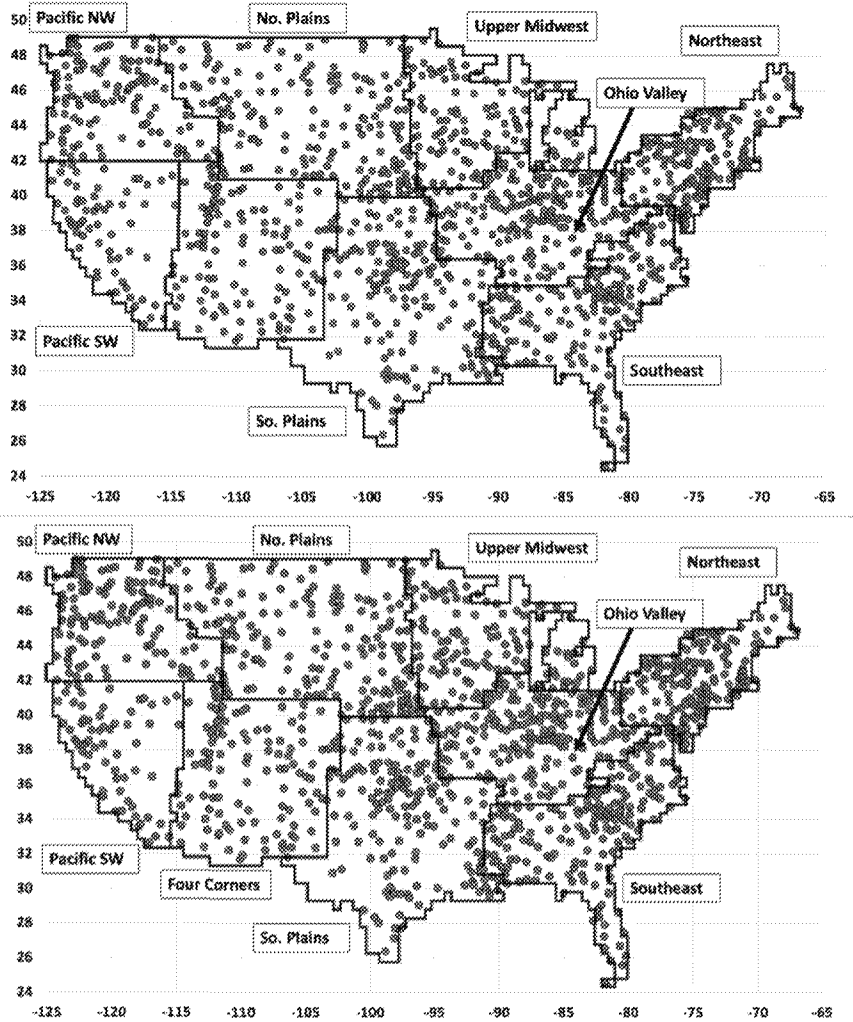


Figure 8.7.34.42 Locations of USHCN temperature stations. Source: USHCN.

We begin with the question of whether the occurrence of daily record high or low temperatures changed has changed since Dec 1898. Each warm-season has 153 days (1 May to 30 Sep) and each cold-season has 122 days (1 Dec to 31 Mar). For each station and day, we calculated the year in which the record highest (lowest) temperature occurred. With 126 years of observations, if there were no temperature trends over time, the expected number of records for TMax would be 1.21 ( $=153/126$ ) per station per year and for TMin 0.96 ( $=122/126$ ) per station per year. Figure 8.7.4-34.3 indicates the observed distribution in time of the occurrence of these extreme events.



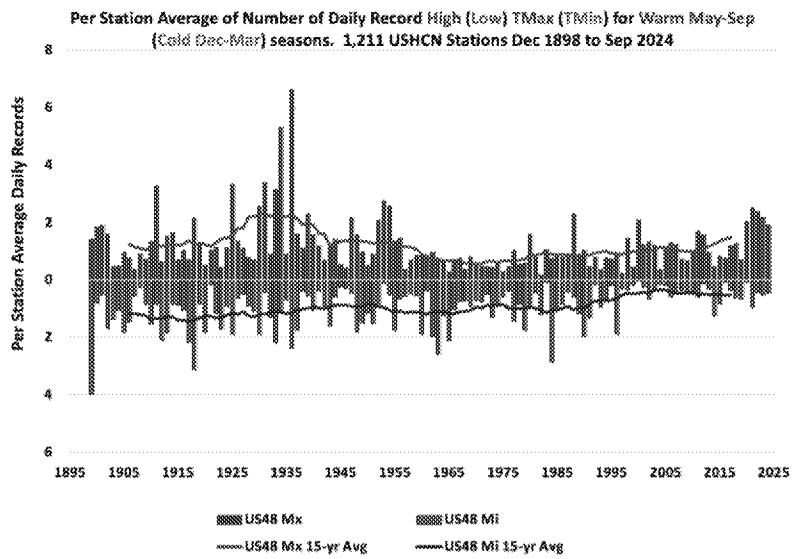


Figure 8-7.34.23 Number of daily record High (red) and Low (blue) for warm and cold seasons in the CONUS. The lines represent the 15-year running, centered average. Source: 1,211 USHCN stations supplemented as needed to achieve a minimum of 92% of observations in the 126-year period since Dec. 1898.

The results indicate a common feature in many metrics of warm-season extremes in the CONUS - the exceptional heat of the 1920s and especially the 1930s, peaking in 1936. On a per-station average, 60% of the TMax records and 59% of the TMin records occurred in the first half of the period (1899-1961).

On the cold side, the Valentine's Day Arctic outbreak in Feb. 1899 stands as the most extensive cold extreme experienced by the CONUS, with 1917 in 2nd place. The frequency of cold records has declined, especially over the last quarter of the period in which only 13% of the extreme cold events were measured. In contrast, 25% of the extreme TMax records were achieved in the last quarter, in accordance with statistical expectations. These general features have been noted in past assessments (see above, IPCC AR5, IPCC AR6, NCA4, NCA5 [7]). Combining the two records the overall reduction in numbers of both cold and hot extremes over the past century indicates a climate less prone to extremes.

This pattern is also shown in Figure 8-7.34.43. For each station and for each year the hottest warm season and coldest cold-season temperatures were calculated and converted to anomalies relative to the station's long-term warm and cold season (respectively) averages. Then the differences between these were computed by station and geographically-averaged over all stations, thus yielding an

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annual measure of the expected range of local extreme temperatures for each year. Figure 8-7.4.4.11 shows the 15-year trailing average of this measure, which has clearly declined over the past century.

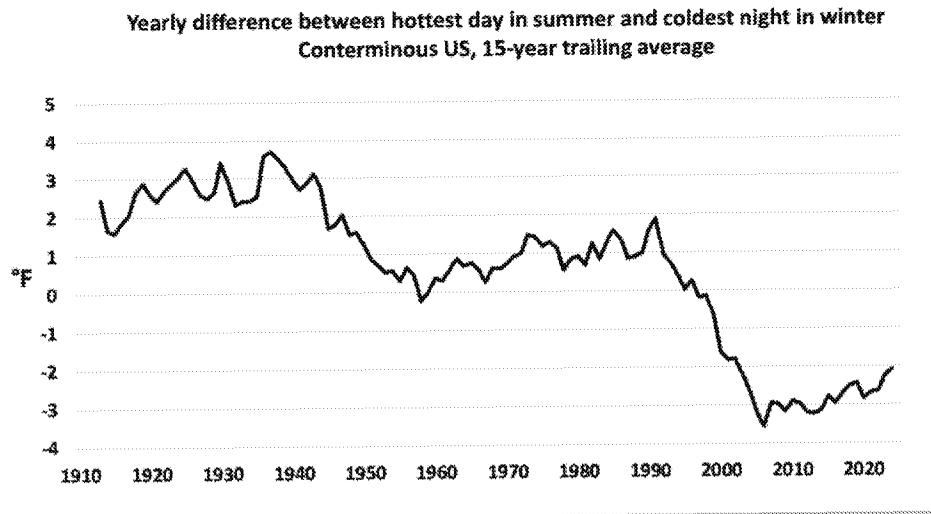


Figure 8-7.4.4.11. 15-year trailing average of the difference each year of each station's hottest warm-season TMax and coldest cold-season TMin relative to the long-term average. Source: USHCN, author calculations.

The average difference for each station between the hottest summer TMax and coldest winter TMin has declined by about 5°F in the past 126 years. The decline is due mostly to warmer winter TMin, but a decline in the magnitude of summer TMax is also a factor. The rise in TMin has been strongly related to the growing presence of manufactured surfaces around the weather stations over the last 100+ years (the so-called urban heat island effect; Spencer et al. 2025).

Summarizing Figures 8-7.4.134.23 and 8-7.4.23.3.4.4, in summary, while temperature extremes are regularly experienced in the US and attract a great deal of media attention, long-term records show the US climate has become less extreme over time (milder) when measured in terms of the range between warm season maxima and cold season minima.

#### 8.7.4.4.2 Exceedances of a heat threshold

Under the heading of "The Risk of Temperature Extremes is Changing", the most recent US National Climate Assessment report (NCA235) notes the increase in a threshold metric of number of days at or above 95°F, stating,

"The western US has been particularly affected by extreme heat since the 1980s ... experiencing a larger increase in days over 95°F, as would be expected given the greater warming in that region relative to the eastern US. Several major heatwaves have affected the US since 2018, including a record-shattering event in the Pacific Northwest in 2021."

Are the occurrences of 95°F days changing? In a climate as varied as that of CONUS, threshold statistics can be misleading. A region with many stations that have near 95°F TMax average temperatures in the summer might see large swings in the metric when only small changes in average temperature occur. Elsewhere with stations that either rarely or virtually always achieve 95°F TMax temperatures, a small change will not impact the results much at all. In the past 126 years, the average CONUS station experienced 129 days exceeding 95°F per 6-yr period, but the regional values range from 278 in the Southern Plains to 9 in the Northeast. Thus, one needs to view such threshold analyses with caution.

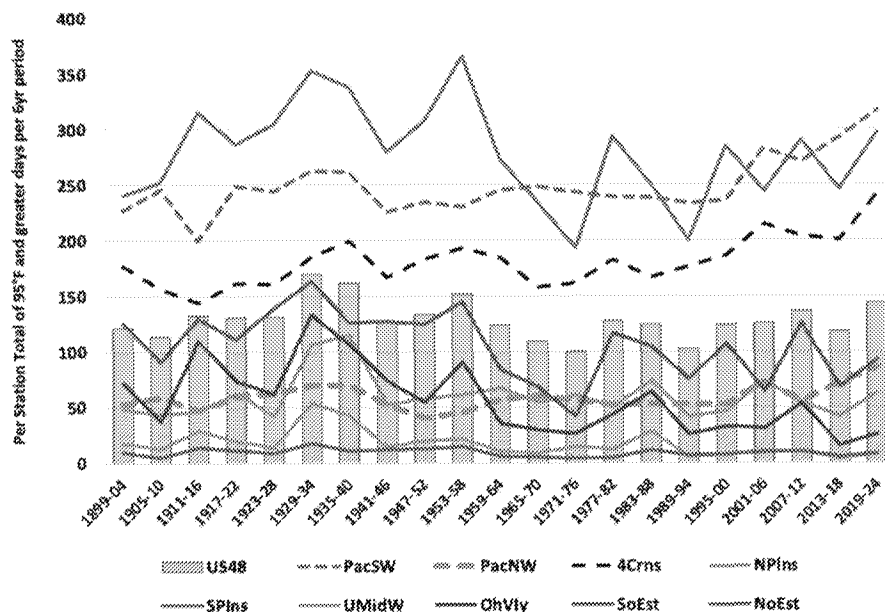


Figure 8.7.4.334.45. Total number of days  $\geq 95^{\circ}\text{F}$  in 6-yr periods. US 48 (bars) and regions (lines). Interval is 6-years as this is divisible into 126. Source: USHCN, author calculations.

In Fig. 8.7.4.334.45 we see that only three of the nine regions, all in the West, have experienced upward trends in the number of 95°F or hotter days (dashed lines). The CONUS, as a whole has not, and the other six regions have experienced declines.

The Pacific NW heatwave of 2021 is referenced as often the NCA523-claim an event we examine more closely in Section 69.4. The evidence indicates that it was a “black swan” event, i.e., a single, unprecedented event in the record, not part of a pattern of increasing extreme heat. For example, the 5-day average tropospheric grid-point temperature anomaly over the Pacific NW during that event was +10.8 C, the most extreme NH Northern Hemisphere grid point summer anomaly in the 46 years from over 4 million grid values. In contrast, the global temperature anomaly during that time was virtually zero (+0.03 C, Mass et al. 2024).

The heading “The Risk of Temperature Extremes is Changing” WHERE IS THIS HEADING FROM suggests positive trends are now being observed in threshold temperatures on a widespread basis, but that is not evidenced in the combined CONUS results of the figures above.

#### 8-7.4.34.3 Heatwaves

Heatwaves (consecutive days that exceed an extreme threshold) have a greater societal impact than a single daily record temperature. We measure “Heatwave Days” here as the count of all days in May-Sep each year that exceed the 90<sup>th</sup> percentile and that lie within a run period of at least six consecutive days. This is equivalent to the method used in NCA517, except that the reference period here is the entire record 1899-2024, while NCA517 truncated the reference period to 1961-1990, a cool period. That truncation boosts positive results (days exceeding the 90<sup>th</sup> percentile) in periods warmer than the reference period, especially starting in 1960 and moving to the present (see *Urban Influences* below).

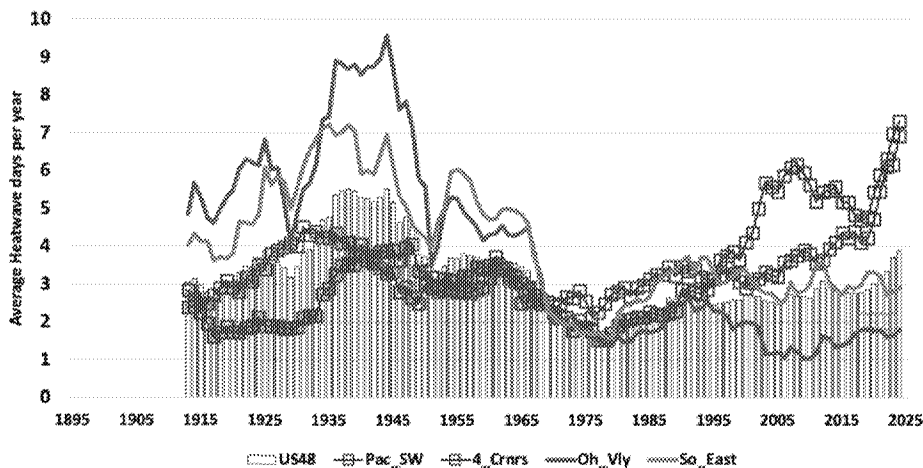


Figure 8-7.4.34.56 15-year trailing average of number of heatwave days per year per station in the CONUS (bars) and four regions: Pac\_SW (purple squares, CA, NV), 4\_Cntrs (red squares, AZ,NM,UT,CO), Oh\_Vly (blue, MO, IL, KY, TN, IN, OH, WV) and So\_East (green, MS, AL, GA, FL, SC, NC, VA).

Figure 8.7.4-124.56 indicates again the excessive heat of the first half of the 20<sup>th</sup> century, primarily in the eastern two-thirds of the nation, as seen in the regional values for the Ohio Valley and the Southeast as examples. The West has seen a recent increase of heatwave days and the two regions with the highest number are shown, the Pacific Southwest and the Four-Corners (NCA523). This indicates that the background warm season circulation favored heatwaves in the eastern portions of the country in the first half of the 20<sup>th</sup> century, but in the 21<sup>st</sup> century the patterns have favored heatwaves in the West. For CONUS as a whole, heatwaves are no more common today than they were a century ago.

Of interest here is the regional variation of this metric. The four northern regions (Pacific NW, Northern Plains, Upper Midwest and Northeast) on average experience 15 to 27 heatwave days per 15-year period. In contrast, the five southern regions (Pacific Southwest, 4-Corners, Southern Plains, Ohio Valley and Southeast) see 37 to 54 such days, essentially twice as many. This suggests the summer circulation pattern is more prone to stationary events in the southern regions while transient systems in the northern regions are more common and thus cut short these potentially longer events.

#### 8.7.3.4.4 Urban influences

The NCA523 directs readers to the website [HYPERLINK "<https://www.globalchange.gov/indicators/heat-waves>"]. (USGCRP 2023) to view the number of urban heatwaves by decade from the 1960s. The figure shows a monotonic increase in each decade from 2 occurrences per year in the 1960s to 6 in the 2020s. The definition of a heatwave is an unusual but practical measure of human discomfort - a period of at least 2 consecutive days when the minimum apparent temperature (combination of temperature and humidity) exceeds the 85<sup>th</sup> percentile. Note too, the dataset is limited to the 50 largest U.S. cities.

These increasing values since 1960 presented in USGCRP (2023) are entirely reasonable, but are unrelated to GHG emissions for at least two reasons. Urbanization in these cities is a major factor in the rise of TMin relative to co-located TMax and relative to TMin at rural stations. Also, the 1960s was the coldest decade and 1970s the second coldest decade since the 1910's, so this starting date preconditions the time series to show increases. This does not dismiss the real rise in nighttime temperatures in major U. S. cities and the societal impacts associated with these changes. However, we note for a variety of reasons, that summer TMax (especially in rural areas) serves as better response variable for detecting potential changes in heatwaves influenced by changes in the background climate due, for example, to increasing GHGs (Christy et al. 2009). For the CONUS as a whole, the evidence in this section suggests GHG emissions have had little-to-no effect on heatwaves.

#### 8.4.Tornadoes

AR6: [O]bservational trends in tornadoes, hail, and lightning associated with severe convective storms are not robustly detected due to inefficient coverage of the long-term observations. There is medium confidence that the mean annual number of tornadoes in the USA has remained relatively constant. (Chapter 11, section 11.7.3, p.1504)

As noted there is no evidence of trends in US tornado or extreme convective storms. Extreme precipitation will be discussed below.

#### 8.7.455 Extreme precipitation

The IPCC AR6 assessed that an increase in heavy precipitation has been observed in data starting in the 1950s.

AR6: "The frequency and intensity of heavy precipitation events have increased since the 1950s over most land area for which observational data are sufficient for trend analysis (high confidence)." (SPM.A3.2)

AR6: "In North America, there is robust evidence that the magnitude and intensity of extreme precipitation has *very likely* increased since the 1950s. Both [one-day maximal and 5-day maxima] have significantly increased in North America during 1950-2018" (Chapter 11, p. 1560)

However other data sources indicate less evidence of increasing extreme precipitation when examined over a longer time scale.

Figure 8.7.45.1 shows that US long term data from NOAA (1895-2023) shows an insignificantly increasing tendency toward extreme wetness (+0.0001% per year)

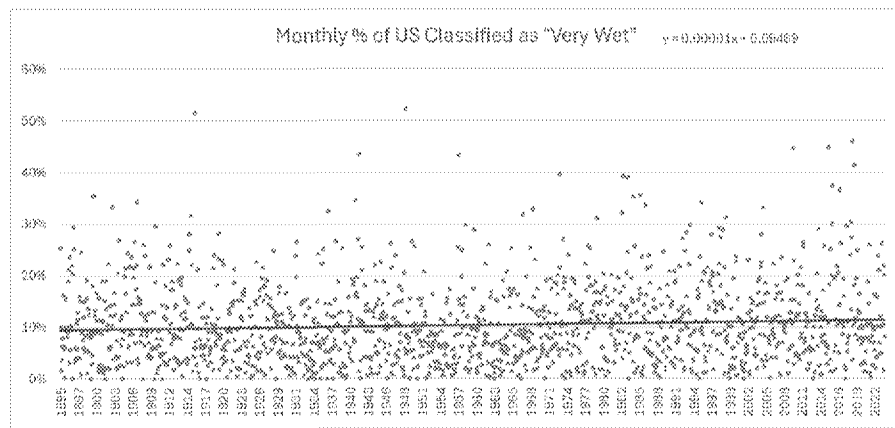


Figure 8.7.45.1: Long term US wetness (%). Source: NOAA [HYPERLINK "<https://www.ncei.noaa.gov/access/monitoring/uspa/wet-dry/0/>"]

Because precipitation involves a discrete phase change (water vapor to liquid), it is stochastic and episodic in character and requires careful statistical treatment to understand variability over long time periods (see 8.7.1 Introduction). The US National Climate Assessments (NCA417, NCA523) have highlighted an increase in the occurrence of the heaviest precipitation events (defined in different ways) primarily in the eastern half of the CONUS, especially the Northeast, when starting the analysis in either 1901 or 1958. Interestingly, the regional variations indicate that the largest increases in

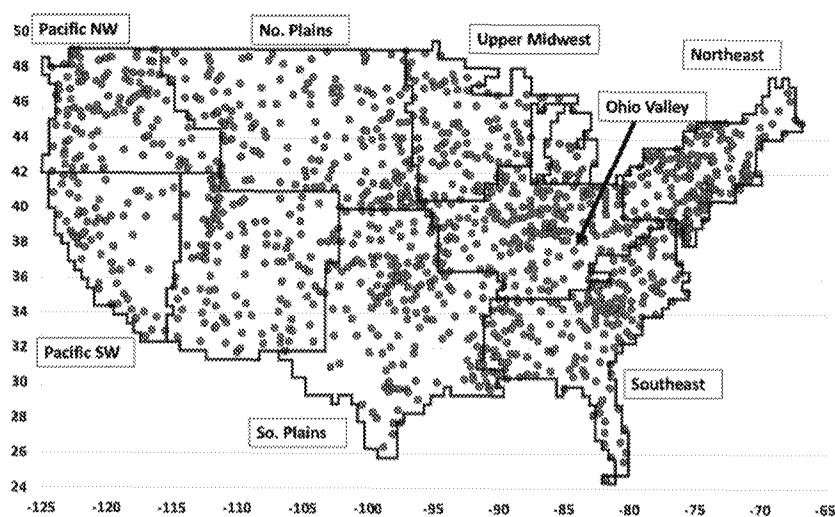
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extreme events are in the Northeast and the smallest in the West, a trend pattern counter to the changes in temperature extremes.



McKittrick and Christy (2019) examined long-term and consistent station observations of extreme daily precipitation to test some of these NCA claims for the Southeast and West Coast. When the time series were extended back in time (as far as 1872 in some cases) or when starting later (1978), there were no significant trends for either region.

For this report we updated these findings with similarly constructed observations from 29 stations on the CONUS Pacific Coast (1893ff from San Diego, CA to Blaine WA) and 24 stations in the humid Southeast (1872ff from Austin TX to Washington DC), and also adding 21 stations in the Northeast (1888ff from Buffalo, NY to Gardiner ME). The locations are shown in Figure 2.5.2. The results of applying the analysis of McKittrick and Christy (2019) were as follows for each region, then indicating the statistical updates followed by further explanations:



{will generate

map of stations - RM}

Figure 7.5.2: Locations of precipitation monitoring stations used in this report. Green: Pacific coast. Blue: Northeast. Red: Southeast.

#### Pacific region:

- The trend in average precipitation is significant (downwards) in Astoria, insignificant elsewhere.
- The trend in rainfall variance is positive and significant in Big Sur, insignificant elsewhere.
- The trend in daily maximum precipitation is positive and significant in Aberdeen and Big Sur and negative and significant in Newport (insignificant elsewhere).
- Averaged over all stations in the region none of these three trend parameters is statistically significant.

#### Southeast region:

- The trend in average precipitation is positive and significant in Mobile and Quitman, insignificant elsewhere.
- The trend in rainfall variance is positive and significant in Mobile, insignificant elsewhere.
- The trend in daily maximum precipitation is positive and significant in Vicksburg and Norfolk, insignificant elsewhere.
- Averaged over all stations in the region none of these three trend parameters is statistically significant.

#### Northeast region:

- The trend in average precipitation is positive and significant in 9 of 21 locations and in the region averaged overall.
- The trend in rainfall variance is positive and significant in Portland, Albany and Buffalo, insignificant elsewhere.
- The trend in daily maximum precipitation is positive and significant in Portland and Gardiner, insignificant elsewhere.
- Averaged over all stations in the region the trend parameters for variance and maximum precipitation are not statistically significant.

#### Pacific Coast heavy rainfall events



- \* Average precipitation trend is significant (downwards) in Astoria OR; insignificant elsewhere.
- \* The trend in rainfall variance is positive and significant in Big Sur CA; insignificant elsewhere.
- \* The trend in daily maximum precipitation is positive and significant in Aberdeen WA and Big Sur CA and negative and significant in Newport OR (insignificant elsewhere).
- \* Averaged over all stations in the region, none of these three trend parameters is statistically significant.

The Pacific Coast receives considerable precipitation from Atmospheric River (AR) events which often last more than a day or two (e.g., Gershunov et al. 2017, Pan et al. 2024). The worst-known such series of events in recent history was the so-called ARek Storm that occurred between December 1861 and January 1862, which dumped nearly 10 feet of rain in parts of California and submerged the entire Central Valley for weeks under as much as 1.5 feet of water (Brewer 1930, Null and Hulbert 2007). Additionally, Paleoclimate research has found six megastorms more severe than 1861-1862 in California during the last 1800 years, occurring at intervals of 300 years or so (Porter et al. 2011).

#### SIDEBAR: Perils of short data records

San Francisco provides a good case study of the limitation of using short historical samples to characterize natural variability of extreme events. Suppose we use a 130-year sample of daily San Francisco precipitation from 1895 to 2024 and we look for 3-day, 5-day, 14-day and 30-day rainfall records. The results are as shown in Table 8-7.2.

| Event  | Record (inches) | Year |
|--------|-----------------|------|
| 3-day  | 6.94            | 2023 |
| 5-day  | 8.55            | 2023 |
| 14-day | 12.62           | 2023 |
| 30-day | 18.93           | 1998 |

Table 8-7.2: Extreme rainfall records, San Francisco, 1895-2024.

The records all cluster in the more recent data. 2023 appears to be an exceptional year and since it is near the end of the sample, it might suggest that the climate has shifted into a more hazardous state, perhaps as a result of human influences. [Note: "2023" indicates the event occurred in the water-year of Aug 2022 to Jul 2023.]

But the picture is very different if we use a sample that begins 85 years earlier, in 1850. Table 8-7.3 shows that the record-setting events then all happened in the 1860s. Furthermore 2023 is now not even in 2<sup>nd</sup> place but falls to 3<sup>rd</sup> or 4<sup>th</sup> place. Also, comparing the records of the two charts, the extreme precipitation events in 1862 and 1867 involved considerably more rainfall than the 1998 and 2023 events, with 14- and 30-day totals about 50 percent higher.

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| Event  | Record (inches) | Year | Rank of 130-yr extreme |
|--------|-----------------|------|------------------------|
| 3-day  | 8.85            | 1867 | 3                      |
| 5-day  | 9.80            | 1867 | 3                      |
| 14-day | 19.05           | 1862 | 4                      |
| 30-day | 28.25           | 1862 | 2                      |

Table 8.7.3: Extreme rainfall records, San Francisco, 1850-2024.

The range of natural variability is made even more remarkable when paleoclimate evidence is examined. Porter et al. (2011) discovered that in the past 1800 years at least six megastorms were more intense than the devastating 1861-62 ARkStorm that struck the region. Evidently such extreme events, “unprecedented” in our 1895-2024 sample, have impacted the region about every 300 years though not since 1895.

This example illustrates the limitations of using relatively short climate periods (~130 years) to assess the character and range of natural variability in general and of extreme events in particular. Accurate representation of the full range of natural variability is necessary for any attribution analyses (see 6.4). Infrastructure planners, emergency management institutions and attribution scientists would understand the significant mischaracterization of the magnitude of a future extreme if based only on the last 130 years. In this case, a single time-sample of 130 years provides an underestimation of the extreme value by up to 50% determined when adding only 45 more years of observations. Compared to millennial-scale paleoclimate evidence, an even greater underestimation would occur. An important lesson is that the climate can deliver great surprises on its own even without human influences.

We examine occurrences of 5-day deluges as follows. In a 130-year span there are 26 5-year intervals. At each location we computed the 5-day precipitation totals throughout the year and selected the 26 highest values. A single year may have more than one of the 26 heaviest. Each of those can be thought of as 1-in-5-year events. If there are no trends in precipitation then the total number of these events across all stations should be evenly spread out over the years. In Fig. 8.7.4-55.1 we show the distribution in time of these events. The deluges associated with the massive 1997-98 El Niño event are readily apparent. While erratic, as is typical of these types of precipitation metrics, there is no indication of a tendency to become more frequent over time.

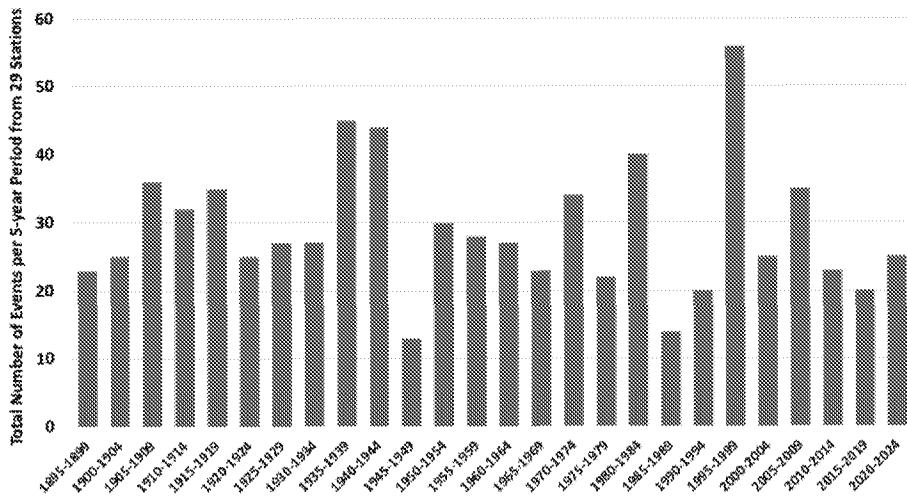


Figure 8-7.5.24-5. The time distribution by 5-year periods of the 26 heaviest occurrences for each station (i.e., nominal 1-in-5 year event) for stations along the Pacific Coast of the CONUS.

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#### *Southeast heavy rainfall events*

- \* The trend in average precipitation is positive and significant in Mobile AL and Quitman GA, and insignificant elsewhere.
- \* The trend in rainfall variance is positive and significant in Mobile AL, insignificant elsewhere.
- \* The trend in daily maximum precipitation is positive and significant in Vicksburg MS and Norfolk VA, and insignificant elsewhere.
- \* Averaged over all stations in the region none of these three trend parameters is statistically significant.

The temporal pattern of 5-day totals of the 1-in-5 yr-year heavy events in the humid Southeast (Figure 8.7.4.65.2) is generally unremarkable, though a cluster of higher values appears in 1995 to 2019. The increase in these years is due largely to the 4 northeastern-most stations of Wilmington NC, Weldon NC, Washington DC, and Norfolk VA. This confirms the pattern indicated in NCA417 and NCA523 of a tendency for an increasing frequency of heavy events, due to a temporal clustering of tropical storms from eastern NC to Maine discussed below. Otherwise, the remaining 20 stations show an unremarkable temporal distribution of heavy events.

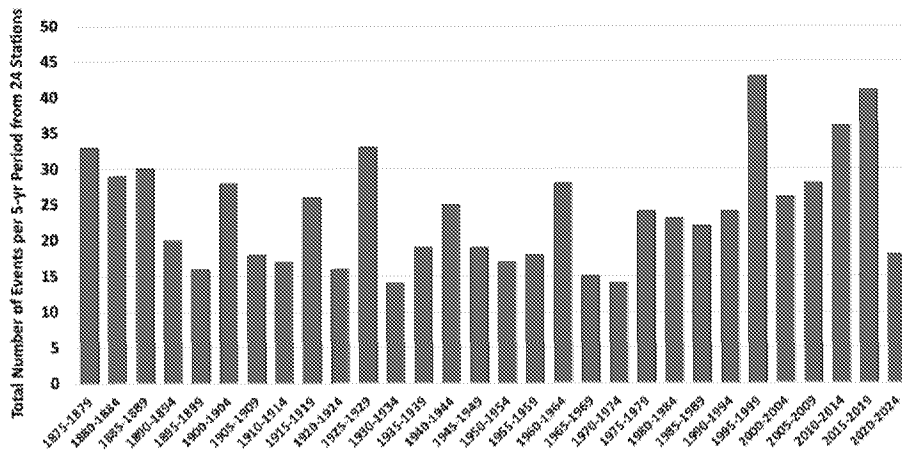


Figure 8-7.4-65.3. As above but for the 30 heaviest 1-in-5yr events for 24 stations in the humid Southeast from Austin TX to Washington DC in 5-year bins for 1875-2024.

#### Northwest heavy rainfall events

- \* The trend in average precipitation is positive and significant in 9 of 21 locations and in the region averaged overall.
- \* The trend in rainfall variance is positive and significant in Portland ME, Albany NY and Buffalo NY; insignificant elsewhere.
- \* The trend in daily maximum precipitation is positive and significant in Portland ME and Gardiner ME; insignificant elsewhere.
- \* Averaged over all stations in the region the trend parameters for variance and maximum precipitation are not statistically significant.

Fig. 8-7.4-75.3 shows the 27 (1-in-5yr) heaviest 3-day events for the last 135 years in 21 stations in the Northeast (including Montreal Canada). We use 3-day totals here as this produced the largest variations in time. In this region, 72% of the events occur during June to October and are dominated by tropical incursions of hurricanes, tropical storms or tropical storms that transition to extratropical systems. According to NCA417 and NCA523 this region experienced the largest increases in extreme events, so it shall be examined more closely.

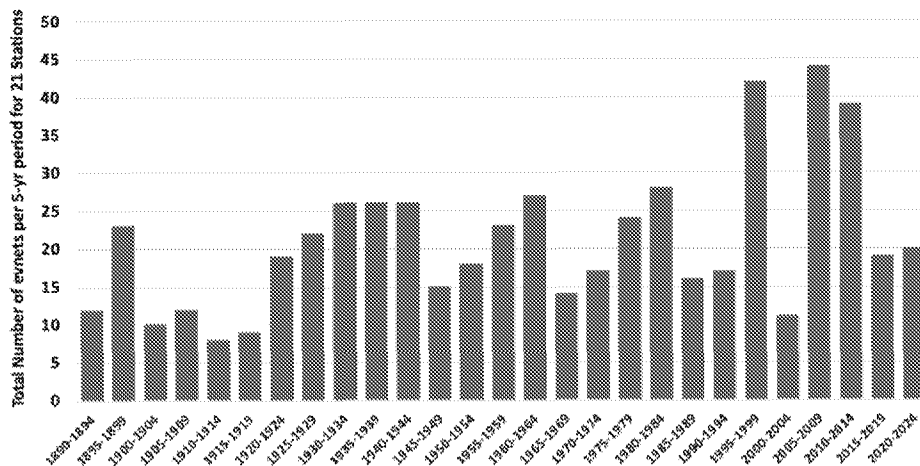


Figure 8-7.4.75.4. Time distribution of the heaviest 27 (1-in-5yr year) heaviest 3-day precipitation events for 21 stations from NY to ME, including Montreal.

Howarth et al. (2019) report differences in the Northeast-between two 18-year periods: 1979-96 and 1997-2014 (a similar region as in Fig. 8-7.4.65.4 that includes PA and NJ) of various precipitation extremes. One metric which indicated a dramatic increase (317%) was found for 24-hr events > 6 inches. This high increase is due to the very small numbers of such events of which there were only 6 in the first period and 25 in the second as reported for 58 stations. This high percentage increase is due to the very small numbers of the events: only 6 in the first period and 25 in the second. Most of the stations did not record such an event suggesting these erratic, episodic events over brief, 18-year periods, need scrutiny by additional statistical methods.

Using the information in Fig. 8-7.4.75.4 over the same years as Howarth et al. we find a 51% increase in the frequency of heavy events between the two periods. One can see in Fig. 8-7.4.65.4 that it was unfortunate that Howarth et al. ended in 2014, prior to a return to the long-term average of such events.

A feature of Howarth et al. is the use of single day totals, which is questionable because extreme events are often spread across the time-of-observation boundary. Thus stations measuring at 0700 Z am LT local time versus those at Midnight will have differing results for a particular event which would then have major impacts on counting these events. We use the 3-day totals in Fig. 8-7.4.75.45 to be sure to capture the extent of these extreme downpours. In any case, we can confirm that the period 1997 to 2014 experienced a cluster of heavier events, as Howarth et al. have documented.

Howarth's most remarkable claim (317% increase in 6" days) is potentially misleading because it is a threshold statistic (see Section section 8-4.2-8-7.3.2 above) and the ratio of small numbers over a short period. The result is not representative of relative extreme events for the whole region, since the majority of stations never experienced a 6" total. Figure 8-7.4.65.5.4 above determines the same number of events for each station (27 heaviest events) whose heaviest values ranged from 4.4" to 12.5" and their 27th heaviest values ranged from 3.3" to 5.0". This analysis thus allows each station to

be equally represented. In other words, if there is a region-wide increase in heavy events, it should be seen in the sum of all stations. Note too that the period of record here is 135 years vs. 36 years of Howarth et al. Except for three 5-year periods between 1995 and 2014, there is nothing statistically remarkable about the results in Fig. 8.7.4.2.

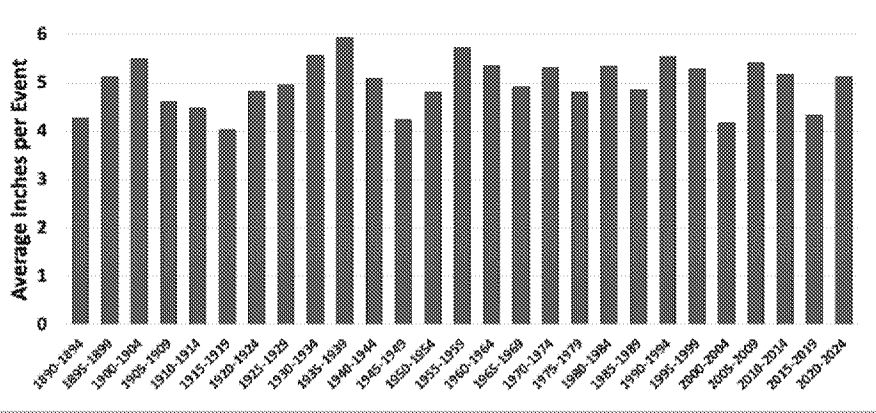


Figure 8.7.4.85.5. Average amount of precipitation falling in the 1-in-5yr events for the NE stations.

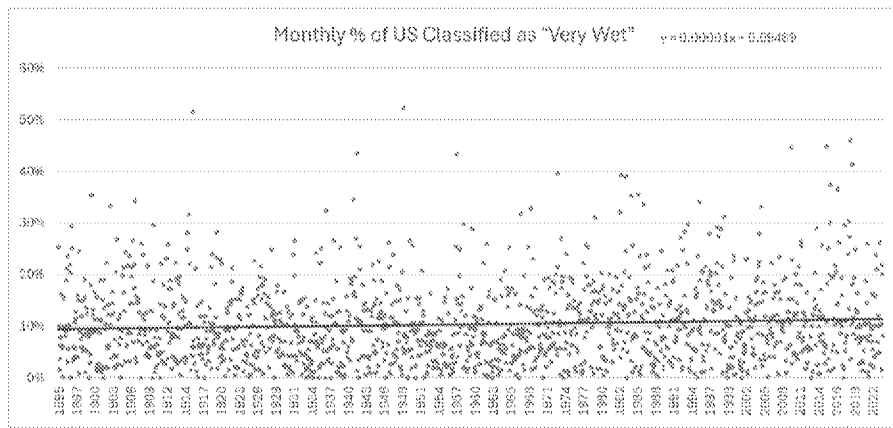
An interesting aspect of Northeast precipitation is that there has been no change in the amount of precipitation per heaviest event, as shown in Fig. 8.7.4.85.5. The trend is only +0.02"/decade. The highest amount, 1935-39, includes the Great New England Hurricane of 1938, one of the rare major (Category 3 or higher) hurricanes to strike the region. The results in Figs. 8.7.4.45.4 and 8.7.4.25.5 suggest that though there was an uptick in the number of events during the period 1995 to 2014, the events individually are not becoming more intense.

long et al. (2024) document the increase of tropical influences on precipitation events in the Northeast since 1959 and concluded, "The autumn extreme precipitation trend over the Northeast US is primarily attributed to tropical cyclone-related events since the 1990s." The question then becomes, was the temporal clustering of tropical systems in 1997-2014 which affected the Northeast a response to increasing GHGs (see Chapter 9 Attribution)? long et al. examined CMIP-6 model output which suggests that there will be fewer such systems in the 21st century but that the intensity of the rainfall events might increase. This conjecture is not seen in Fig. 8.7.4.25.5 where the amount-per-event has remained steady over the 135-year period.

For substantial urban areas (There is some evidence to indicate the heaviest rainfall events may be redistributed due to the impact urban infrastructure has on the local weather (e.g., Pielke Sr. et al. 2011, Zhang et al. 2018, Yang et al. 2024). Yang et al. state, "Cities that experience compact development tend to witness larger increases in extreme rainfall frequency over downtown than their rural surroundings, while the anomalies in extreme rainfall frequency diminish for cities with

dispersed development." While this is an important insight to consider, the effect on the specific stations used in this analysis is unknown, or at least not detectable in Fig. 8.7.4.25.5.

In summary, the evidence from the historical record of extreme precipitation events in the CONUS is generally not consistent from region to region so that inferences regarding trends and their projections are wrought with significant uncertainty. In most regions and perhaps all, it is our analysis here opinion suggests that given the very nature of the erratic and episodic character of extreme precipitation events, changes that can be confidently categorized as significant relative to natural variability have not been observed renders the discovery of statistically significant changes, including a relationship to CO2 concentrations, a result yet to be achieved (McKirk and Christy 2019).



#### 8.7.6 Tornadoes

AR6: [O]bservational trends in tornadoes, hail, and lightning associated with severe convective storms are **not robustly detected** due to insufficient coverage of the long-term observations. There is *medium confidence* that the mean annual number of tornadoes in the USA has remained relatively constant. (Chapter 11, section 11.7.3, p. 1594)

As noted, there is no evidence of trends in US tornadoes or extreme convective storms.

Figure 8.3.84-1: Long-term US wetness (%). Source: NOAA [HYPERLINK "<https://www.ncei.noaa.gov/access/monitoring/uspa/wet-dry/0>"]

#### 9.7.2.27 Flooding

Changes in floods were assessed as follows:

AR6: "The SREX assessed *low confidence* for observed changes in the magnitude or frequency of floods at the global scale. This assessment was confirmed by the AR5 report. The SR1.5 found increases in flood frequency and extreme streamflow in some regions, but decreases in other regions. . . [H]ydrological literature on observed flood changes is heterogeneous, focusing at regional and sub-regional basin scales, making it difficult to synthesise at the global and sometimes regional scales." (Chapter 11.5)

AR6: "The seasonality of floods has changed in cold regions where snowmelt dominates the flow regime in response to warming (*high confidence*). Confidence about peak flow trends over past decades on the global scale is *low*." (Chapter 11.5)

NCA17: "Trends in extreme high values of streamflow are mixed across the United States. Analysis of 200 U.S. stream gauges indicates areas of both increasing and decreasing flooding magnitude but does not provide robust evidence that these trends are attributable to human influences" (pp. 240-241)

The absence of detectable US-wide trends in flooding is consistent with the findings in the previous section of absence of coherent changes in extreme precipitation.

SREX (p. 176)

In the United States and Canada during the 20th century and in the early 21st century, there is no compelling evidence for climate-driven changes in the magnitude or frequency of floods.

AR5 (p. 214)

AR4 WGI Chapter 3 (Trenberth et al., 2007) did not assess changes in floods but AR4 WGI concluded that there was not a general global trend in the incidence of floods (Kundzewicz et al., 2007). SREX went further to suggest that there was low agreement and thus *low confidence* at the global scale regarding changes in the magnitude or frequency of floods or even the sign of changes.

AR5 WGI assesses floods in regional detail accounting for the fact that trends in floods are strongly influenced by changes in river management (see also Section 2.5.2). Although the most evident flood trends appear to be in northern high latitudes, where observed warming trends have been largest, in some regions no evidence of a trend in extreme flooding has been found, for example, over Russia based on daily river discharge (Shildomanov et al., 2007). Other studies for Europe (Hennaford and Marsh, 2008; Renard et al., 2009; Petrow and Mery,



2009; Stahl et al., 2010) and Asia (Jiang et al., 2008; Delgado et al., 2010) show evidence for upward, downward or no trend in the magnitude and frequency of floods, so that there is currently no clear and widespread evidence for observed changes in flooding except for the earlier spring flow in snow-dominated regions (Senewiratne et al., 2012). In summary, there continues to be a lack of evidence and thus *low confidence* regarding the sign of trend in the magnitude and/or frequency of floods on a global scale.

#### AR6 (Ch. 11 p. 1549)

The SR5X (Senewiratne et al., 2012) assessed *low confidence* for observed changes in the magnitude or frequency of floods at the global scale. This assessment was confirmed by the AR5 report (Hartmann et al., 2013). The SR15 (Gleason-Goldberg et al., 2018) found increases in flood frequency and extreme streamflow in some regions, but decreases in other regions. While the number of studies on flood trends has increased since the AR5 report, and there were also new analyses after the release of SR15 (Berghuijs et al., 2017; Blöschl et al., 2019; Gudmundsson et al., 2019), hydrological literature on observed flood changes is heterogeneous, focusing at regional and sub-regional basin scales, making it difficult to synthesise at the global and sometimes regional scales.

In summary, the seasonality of floods has changed in cold regions where snowmelt dominates the flow regime in response to warming (*high confidence*). Confidence about peak flow trends over past decades on the global scale is *low*, but there are regions experiencing increases, including parts of Asia, southern South America, the northeast USA, northwestern Europe, and the Amazon, and regions experiencing decreases, including parts of the Mediterranean, Australia, Africa, and the southwestern USA.

#### US NCA17 pp. 240-41:

"The IPCC AR5 did not attribute changes in flooding to anthropogenic influence nor report detectable changes in flooding magnitude, duration, or frequency. Trends in extreme high values of streamflow are mixed across the United States. Analysis of 200 U.S. stream gauges indicates areas of both increasing and decreasing flooding magnitude, but does not provide robust evidence that these trends are attributable to human influences."

The complex mix of processes complicates the formal attribution of observed flooding trends to anthropogenic climate change and suggests that additional scientific rigor is needed in flood attribution studies. As noted above, precipitation increases have been found to strongly influence changes in flood statistics. However, in U.S. regions, no formal attribution of precipitation changes to anthropogenic forcing has been made so far, so indirect attribution of flooding changes is not possible. Hence, no formal attribution of observed flooding changes to anthropogenic forcing has been claimed."

### 8.2.3 Heatwaves

#### AR5 (p. 212 WG1)

Table 2.13 shows that there has been a *likely* increasing trend in the frequency of heatwaves since the middle of the 20th century in Europe and Australia and across much of Asia where there are sufficient data. However, confidence on a global scale is *medium* owing to lack of studies over Africa and South America but also in part owing to differences in trends depending on how heatwaves are defined (Perkins et al., 2012). Using monthly means as a proxy for heatwaves Gougeon et al. (2013) and Hansen et al. (2012) indicate that record-

breaking temperatures in recent decades substantially exceed what would be expected by chance; but caution is required when making inferences between these studies and those that deal with multi-day events and/or use more complex definitions for heatwave events. There is also evidence in some regions that periods prior to the 1950s had more heatwaves (e.g., over the USA, the decade of the 1930s stands out and is also associated with extreme drought conditions (Peterson et al., 2013) whereas conversely in other regions heatwave trends may have been underestimated owing to poor quality and/or consistency of data (e.g., Della Morte et al. (2007a) over Western Europe; Kuglitich et al. (2009, 2010) over the Mediterranean). Recent available studies also suggest that the number of cold spells has reduced significantly since the 1950s (Donat et al., 2013a, 2013c).

In summary, new analyses continue to support the AR4 and SREX conclusions that since about 1950 it is *very likely* that the numbers of cold days and nights have decreased and the numbers of warm days and nights have increased overall on the global scale; that is, for land areas with sufficient data. It is *likely* that such changes have also occurred across most of North America, Europe, Asia and Australia.

#### NCA12 (pp. 190-191)

Changes in warm extremes are more nuanced than changes in cold extremes. For instance, the warmest daily temperature of the year increased in some parts of the West over the past century (Figure 6.2), but there were decreases in almost all locations east of the Rocky Mountains. In fact, all eastern regions experienced a net decrease (Table 6.2), most notably the Midwest (about 2.2°F [1.2°C]) and the Southeast (roughly 1.5°F [0.8°C]). The decreases in the eastern half of the Nation, particularly in the Great Plains, are mainly tied to the unprecedented summer heat of the 1930s Dust Bowl era, which was exacerbated by land-surface feedbacks driven by springtime precipitation deficits and land mismanagement. However, anthropogenic aerosol forcing may also have reduced summer temperatures in the Northeast and Southeast from the early 1950s to the mid-1970s, and agricultural intensification may have suppressed the hottest extremes in the Midwest.

Since the mid-1960s, there has been only a very slight increase in the warmest daily temperature of the year (amidst large interannual variability). Heat waves (6-day periods with a maximum temperature above the 90th percentile for 1961–1990) increased in frequency until the mid-1920s, became considerably less common through the mid-1960s, and increased in frequency again thereafter (Figure 6.4). As with warm daily temperatures, heat wave magnitude reached a maximum in the 1930s.

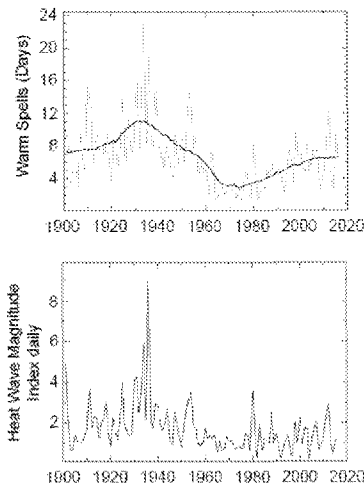


Figure 8.2.1: US Heat waves since 1900. Source: NCA17 Figure 6.4

AR6 (p. 1550)

In North America (Table 11.19), there is very robust evidence for a *very likely* increase in the intensity and frequency of hot extremes and decrease in the intensity and frequency of cold extremes for the whole continent, though there are substantial spatial and seasonal variations in the trends. Minimum temperatures display warming consistently across the continent, while there are more contrasting trends in the annual maximum daily temperatures in parts of the USA (Figure 11.9; Lee et al., 2014; van Oldenborgh et al., 2019; Dunn et al., 2020).

#### 8.2.4 Extreme snowfall events

Note: extreme snowfall events in the US northeast are assessed in relation to winter Extratropical Cyclone (ETC) activity.

AR6 Ch 11, p. 1593

There is *high confidence* that snowfall associated with winter ETCs will decrease in the future, because increases in tropospheric temperatures lead to a lower proportion of precipitation falling as snow (O’Gorman, 2014; Rhoades et al., 2018; Zarzycki, 2018). However, there is *medium confidence* that extreme snowfall events associated with winter ETCs will change little in regions where snowfall will be supported in the future (O’Gorman, 2014; Zarzycki, 2018).

#### 8.2.5 Extreme precipitation

#### SREX (p. 143)

Recent studies have updated the assessment of the AR4, with more regional results now available (Table 3-2). Overall, this additional evidence confirms that more locations and studies show an increase than a decrease in extreme precipitation, but that there are also wide regional and seasonal variations, and trends in many regions are not statistically significant (Table 3-2). Based on station data from Canada, the United States, and Mexico, Peterson et al. (2008a) reported that heavy precipitation has been increasing over 1950–2004, as well as the average amount of precipitation falling on days with precipitation.

#### AR5 (pp. 212–14)

In summary, further analyses continue to support the AR4 and SREX conclusions that it is likely that since 1951 there have been statistically significant increases in the number of heavy precipitation events (e.g., above the 95th percentile) in more regions than there have been statistically significant decreases, but there are strong regional and subregional variations in the trends. In particular, many regions present statistically non-significant or negative trends, and, where seasonal changes have been assessed, there are also variations between seasons (e.g., more consistent trends in winter than in summer in Europe). The overall most consistent trends towards heavier precipitation events are found in central North America (very likely increases) but assessment for Europe shows likely increases in more regions than decreases.

#### AR6 (p. 1560)

In North America, there is robust evidence that the magnitude and intensity of extreme precipitation has very likely increased since the 1950s. Both [one-day maximum and 15-day maximum] have significantly increased in North America during 1950–2012 (Sun et al., 2020, also Figure 11.11). There is, however, regional diversity. In Canada, there is a lack of detectable trends in observed annual maximum daily (or shorter duration) precipitation (Shephard et al., 2014; Makis et al., 2015; Vincent et al., 2016).

#### NC417 pp. 213–14

Detectability of trends (compared to internal variability) for a number of precipitation metrics over the continental United States has been examined; however, trends identified for the U.S. regions have not been clearly attributed to anthropogenic forcing. One study concluded that increasing precipitation trends in some north-central U.S. regions and the extreme annual anomalies there in 2013 were at least partly attributable to the combination of anthropogenic and natural forcing. Based on current evidence, it is concluded that detectable but not attributable increases in mean precipitation have occurred over parts of the central United States. Formal detection-attribution studies indicate a human contribution to extreme precipitation increases over the continental United States, but confidence is low based on those studies alone due to the short observational period, high natural variability, and model uncertainty.

In summary, based on available studies, it is concluded that for the continental United States there is high confidence in the detection of extreme precipitation increases, while there is low confidence in attributing the extreme precipitation changes purely to anthropogenic forcing.

#### 8.2.6 Tornadoes and severe convective storms

Severe convective storms are convective systems that are associated with extreme phenomena such as tornadoes, hail, heavy precipitation (rain or snow), strong winds, and lightning.

The assessment of changes in severe convective storms in SREX (Chapter 3, Seneviratne et al., 2012) and AR5 (Chapter 12, Collins et al., 2013) is limited and focused mainly on tornadoes and hail storms. The SREX assessed that there is *low confidence in observed trends in tornadoes and hail* because of data inhomogeneities and inadequacies in monitoring systems. Subsequent literature assessed in the Climate Science Special Report (Kossin et al., 2017) led to the assessment of the observed tornado activity over the 2000s in the USA, with a decrease in the number of days per year with tornadoes and an increase in the number of tornadoes on these days (*medium confidence*). However, there is *low confidence in past trends for hail and severe thunderstorm winds*. Climate models consistently project environmental changes that would support an increase in the frequency and intensity of severe thunderstorms that combine tornadoes, hail, and winds (*high confidence*), but there is *low confidence* in the details of the projected increase.

In summary, because the definition of severe convective storms varies depending on the literature and the region, it is not straightforward to make a synthesizing view of observed trends in severe convective storms in different regions. In particular, observational trends in tornadoes, hail, and lightning associated with severe convective storms are not robustly detected due to insufficient coverage of the long-term observations. There is *medium confidence* that the mean annual number of tornadoes in the USA has remained relatively constant, but their variability of occurrence has increased since the 1970s, particularly over the 2000s, with a decrease in the number of days per year and an increase in the number of tornadoes on these days (*high confidence*). Detected tornadoes have also increased in Europe, but the trend depends on the density of observations.

In summary, it is extremely difficult to detect and attribute changes in severe convective storms. There is limited evidence that extreme precipitation associated with severe convective storms has increased in some cases.

## 8.2.7 Hurricanes and Tropical Cyclones

SREX (p. 150):

There have been no significant trends observed in global tropical cyclone frequency records, including over the present 40-year period of satellite observations (e.g., Webster et al., 2005). Regional trends in tropical cyclone frequency have been identified in the North Atlantic, but the fidelity of these trends is debated (Holland and Webster, 2007; Landsea, 2007; Mann et al., 2007a). Different methods for estimating undercounts in the earlier part of the North Atlantic tropical cyclone record provide mixed conclusions (Chang and Gao, 2007; Mann et al., 2007b; Kunkel et al., 2008; Vecchi and Knutson, 2008). Regional trends have not been detected in other oceans (Chan and Xu, 2009; Kubota and Chan, 2009; Callaghan and Power, 2011). It thus remains uncertain whether any observed increases in tropical cyclone frequency on time scales longer than about 40 years are robust after accounting for past changes in observing capabilities (Knutson et al., 2010).

AR5 (pp. 316–17):

Current data sets indicate no significant observed trends in global tropical cyclone frequency over the past century and it remains uncertain whether any reported long-term increases in tropical cyclone frequency are robust after accounting for past changes in observing capabilities (Knutson et al., 2010). No robust trends in annual numbers of tropical storms, hurricanes and major hurricanes counts have been identified over the past 100 years in the North Atlantic basin. Measures of land-falling tropical cyclone frequency (Figure 2.24) are generally considered to be more reliable than counts of all storms which tend to be strongly influenced by those that are weak and/or short-lived. Callaghan and Power (2011) find a statistically significant decrease in Eastern Australia land-falling tropical cyclones since the late 19th century although including 2010/2011 season data this trend becomes non-significant (i.e., a trend of zero lies just inside the 90% confidence interval). Significant trends are not found in other oceans on shorter time scales (Chan and Xu, 2009; Kubota and Chan, 2009; Mohapatra et al., 2011; Weinkle et al., 2012), although Grinstead et al. (2012) find a significant positive trend in eastern USA using tide gauge data from 1923–2009 as a proxy for storm surges associated with land-falling hurricanes. Differences between tropical cyclone studies highlight the challenges that still lie ahead in assessing long-term trends.

In summary, this assessment does not revise the SREX conclusion of low confidence that any reported long-term (centennial) increases in tropical cyclone activity are robust after accounting for past changes in observing capabilities. More recent assessments indicate that it is *unlikely* that annual numbers of tropical storms, hurricanes and major hurricanes counts have increased over the past 100 years in the North Atlantic basin. Evidence, however, is for a virtually certain increase in the frequency and intensity of the strongest tropical cyclones since the 1970s in that region.

AR6 (p. 1525)

There is low confidence in most reported long-term (multidecadal to centennial) trends in TC frequency or intensity-based metrics due to changes in the technology used to collect the best-track data. This should not be interpreted as implying that no physical (real) trends exist, but rather as indicating that either the quality or the temporal length of the data is not adequate to provide robust trend detection statements, particularly in the presence of multidecadal variability.

There are previous and ongoing efforts to homogenize the best-track data (Elsner et al., 2008; Kossin et al., 2013, 2020; Choy et al., 2015; Landsea, 2015; Emanuel et al., 2018) and there is substantial literature that finds positive trends in intensity-related metrics in the best-track during the “satellite period”, which is generally limited to the past ~40 years (Kang and Elsner, 2012; Kishinawa et al., 2012; Kossin et al., 2013, 2020; Mei and Xie, 2016; Zhao et al., 2018; Tawale and Touboli, 2019). When best-track trends are tested using homogenized data, the intensity trends generally remain positive, but are smaller in amplitude (Kossin et al., 2013; Holland and Bruyère, 2014). Kossin et al. (2020) extended the homogenized TC intensity record to the period 1979–2017 and identified significant global increases in major TC exceedance probability of about 6% per decade. In

<sup>6</sup>The underlined text referenced a study (Kossin et al. 2020) that later retracted a portion of its findings. Those authors assembled a data set on global TC incidence spanning 1979 to 2017 from which they claimed that the global fraction of TCs reaching major damage (Cat 3–5) rose from 2.7% during 1979–1997 to 3.1% during 1998–2017 and that the increase was statistically significant. However, closer examination of their results showed a significant increase only in the North Atlantic (1.6% to 3.4%) whereas changes in all other basins (Eastern

addition to trends in TC intensity, there is evidence that TC intensification rates and the frequency of rapid intensification events have increased within the satellite era (Kishtawal et al., 2012; Balaguru et al., 2018; Bhatia et al., 2018). The increase in intensification rates is found in the best tracks as well as the homogenized intensity data.

~~A subset of the best-track data corresponding to hurricanes that have directly impacted the United States since 1900 is considered to be reliable, and shows no trend in the frequency of U.S. landfall events (Knutson et al., 2019).~~

### 8.7.2.868 Droughts

Assessments of drought trends were as follows:

AR6: "Few AR6 regions show observed increases in meteorological drought" (Section 11.9, p. 1575).

AR6: "Increasing trends in agricultural and ecological droughts have been observed on all continents (*medium confidence*), but decreases only in one AR6 region (*medium confidence*). Increasing trends in hydrological droughts have been observed in a few AR6 regions." (Chapter 11 Summary)

NCA17: "As a consequence of this increased precipitation, drought statistics over the entire CONUS have declined." (p. 233)

NCA17: "Recent droughts and associated heat waves have reached record intensity in some regions of the United States; however, by geographical scale and duration, the Dust Bowl era of the 1930s remains the benchmark drought and extreme heat event in the historical record (very high confidence)." (p. 231)

SREX: "From a paleoclimate perspective, recent droughts are not unprecedented, with severe 'megadroughts' reported in the paleoclimatic record for Europe, North America, and Australia." (p. 170)

US NCA17 REPORT (Ch. 8, Wehner et al. 2017)  
p. 231:

Recent droughts and associated heat waves have reached record intensity in some regions of the United States; however, by geographical scale and duration, the Dust Bowl era of the 1930s remains the benchmark drought and extreme heat event in the historical record (very high confidence). While by some measures drought has decreased over much of the continental United States in association with long-term increases in precipitation,

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*Red Sea, Western Pacific, North Indian, South Indian, South Pacific) were not statistically significant in a subsequent correction ([HYPERLINK "<https://www.pnas.org/doi/10.1073/pnas.2021573117>"]. Kossin et al. stated that the global probability of observing a major TC rose from 24% during 1979-1997 to 27% in the same period and that the evidence for statistical significance was now weaker. Nevertheless, the authors claimed that the correction did not affect their conclusions.*

neither the precipitation increases nor inferred drought decreases have been confidently attributed to anthropogenic forcing.

The human effect on recent major U.S. droughts is complicated. Little evidence is found for a human influence on observed precipitation deficits, but much evidence is found for a human influence on surface soil moisture deficits due to increased evapotranspiration caused by higher temperatures. (High confidence)

p. 232:

Drought is, of course, directly connected to seasonal precipitation totals. Figure 7-1 shows detectable observed recent changes in seasonal precipitation. In fact, the increases in observed summer and fall precipitation are at odds with the projections in Figure 7-5. As a consequence of this increased precipitation, drought statistics over the entire CONUS have declined.

SREX (p. 170)

From a paleoclimate perspective recent droughts are not unprecedented, with severe 'megadroughts' reported in the paleoclimatic record for Europe, North America, and Australia (Jansen et al., 2007). Recent studies extend this observation to African and Indian droughts (Sinha et al., 2007; Shanshan et al., 2009); much more severe and longer droughts occurred in the past centuries with widespread ecological, political, and socioeconomic consequences. Overall, these studies confirm that in the last millennium several extreme droughts have occurred (Brède and Badeau, 2008; Kuttel, 2008; Rüntgen et al., 2010).

In North America, there is *medium confidence* that there has been an overall slight tendency toward less dryness (wetting trend with more soil moisture and runoff Table 3-2), although analyses for some subregions also indicate tendencies toward increasing dryness. This assessment is based on several lines of evidence, including simulations with different hydrological models as well as PDSI and GDD estimates (Alexander et al., 2006; Andreadis and Lettenmaier, 2006; van der Schrier et al., 2006a; Kunkel et al., 2008; Sheffield and Wood, 2008a; Dai, 2011).

The most severe droughts in the 20th century have occurred in the 1930s and 1950s, where the 1930s Dust Bowl was most intense and the 1950s drought most persistent (Andreadis et al., 2005) in the United States, while in Mexico the 1950s and late 1990s were the driest periods. Recent regional trends toward more severe drought conditions were identified over southern and western Canada, Alaska, and Mexico, with subregional exceptions (Dai, 2011).

SREX (p. 172)

Overall, though new studies have furthered the understanding of the mechanisms leading to drought, there is still relatively limited evidence to provide an attribution of observed changes, in particular given the issues associated with the availability of observational data (Section 3.2.1) and the definition and computation of drought indicators (Box 3-3). This latter point was mostly identified in post-AR4 studies (Box 3-3). Moreover, regions where consistent increases in drought are identified (see 'Observed Changes') are only partly consistent with those where projections indicate an enhancement of drought conditions in coming decades (see next paragraph). We thus assess that there is *medium confidence* (see also Section 3.1.5) that anthropogenic influence has contributed to some



changes in the drought patterns observed in the second half of the 20<sup>th</sup> century, based on its attributed impact on precipitation and temperature changes (though temperature can only be indirectly related to drought trends; see Box 3-3). However there is low confidence in the attribution of changes in droughts at the level of individual regions.

#### AR5 (pp. 214-215)

Based on evidence since AR4, SREX concluded that there were not enough direct observations of dryness to suggest high confidence in observed trends globally, although there was medium confidence that since the 1950s some regions of the world have experienced more intense and longer droughts. The differences between AR4 and SREX are due primarily to analyses post-AR4, differences in how both assessments considered drought and updated IPCC uncertainty guidance.

Because drought is a complex variable and can at best be incompletely represented by commonly used drought indices, discrepancies in the interpretation of changes can result. For example, Sheffield and Wood (2008) found decreasing trends in the duration, intensity and severity of drought globally. Conversely, Dai (2011a,b) found a general global increase in drought, although with substantial regional variation and individual events dominating trend signatures in some regions (e.g., the 1970s prolonged Sahel drought and the 1930s drought in the USA and Canadian Prairies). Studies subsequent to these continue to provide somewhat different conclusions on trends in global droughts and/or dryness since the middle of the 20<sup>th</sup> century (Sheffield et al., 2012; Dai, 2013; Donat et al., 2013c; van der Schrier et al., 2013).

In summary, the current assessment concludes that there is not enough evidence at present to suggest more than low confidence in a global-scale observed trend in drought or dryness (lack of rainfall) since the middle of the 20<sup>th</sup> century, owing to lack of direct observations, geographical inconsistencies in the trends, and dependence of inferred trends on the index choice. Based on updated studies, AR4 conclusions regarding global increasing trends in drought since the 1970s were probably overstated. However, it is likely that the frequency and intensity of drought has increased in the Mediterranean and West Africa and decreased in central North America and north-west Australia since 1950.

#### AR6 (Drought, Observed trends, Section 11.6.2, pp. 1572-75)

##### p-1572

Strong precipitation deficits have been recorded in recent decades in the Amazon (2005-2010), south-western China (2009-2010), south-western North America (2011-2014), Australia (1997-2009), California (2014), the middle East (2012-2016), Chile (2010-2015), the Great Horn of Africa (2011), among others (van Dijk et al., 2013; Mann and Gleick, 2015; Rowell et al., 2015; Marengo and Espinoza, 2016; Dai and Zhao, 2012; Garreaud et al., 2012, 2020; Marengo et al., 2017; Brito et al., 2018; Cook et al., 2018). Global studies generally show no significant trends in SPI time series (Orlowsky and Senaviratne, 2013; Spinoni et al., 2014), and in derived drought frequency and severity data (Spinoni et al., 2019), with very few regional exceptions (Section 11.9 and Figure 11.17).

##### p-1574

For AR6 regions, several studies suggest an increase in the frequency and areal extent of soil moisture deficits, with examples in East Asia (Cheng et al., 2015; Y. Qin et al., 2015; Jia et al., 2019), Western and Central Europe (Trnka et al., 2015b), and the Mediterranean (Hanel et

al., 2018; Moravec et al., 2019; Markonis et al., 2021). Nonetheless, some analyses also show no long-term trends in soil drying in some AR6 regions—for example, in Eastern North America (Park Williams et al., 2017) and Central North America (Senger et al., 2019), as well as in North Eastern Africa (Kew et al., 2021).

There is evidence based on streamflow records of increased hydrological droughts in East Asia (D. Zhang et al., 2018) and southern Africa (Gudmundsson et al., 2019). In areas of Western and Central Europe and Northern Europe, there is no evidence of changes in the severity of hydrological droughts since 1950 based on flow reconstructions (Gillieset et al., 2017; Barker et al., 2019) and observations (Vicente-Serrano et al., 2019). In North America, depending on the methods, datasets and study periods, there are differences between studies that suggest an increase (Shukla et al., 2015; Udall and Overpeck, 2017) versus a decrease in hydrological drought frequency (Mo and Lettenmaier, 2018), but in general there is strong spatial variability (Pashiri and Pol, 2016). Streamflow observation reference networks of near-natural catchments have also been used to isolate the effect of climate trends on hydrological drought trends in a few regions, but these show limited trends in Northern Europe and Western and Central Europe (Stahl et al., 2010; Bard et al., 2015; Harrigan et al., 2018), North America (Dudley et al., 2020) and most of Australia, with the exception of Eastern and Southern Australia (X.S. Zhang et al., 2016).

#### p.1575

Few AR6 regions show observed increases in meteorological drought (Section 11.9), mostly in Africa and South America (NES; *high confidence*; WAF, CAE, ESAF, SAM, SMS, SSA, SAS; *medium confidence*); a few others show a decrease (WSB, ESE, NAL, CAU, NEU, CNA; *medium confidence*). There are stronger signals indicating observed increases in agricultural and ecological drought (Section 11.9), which highlights the role of increased [evapotranspiration] driven by increased [atmospheric evaporative demand] for these trends (Sections 11.6.2.3, 11.6.2.5). Past increases in agricultural and ecological droughts are found on all continents and several regions (WAF, CAE, WSAR, ESAF, WCA, ECA, EAS, SALL, MED, WCE, NES; *medium confidence*), while decreases are found only in one AR6 region (NAL; *medium confidence*). The more limited availability of datasets makes it more difficult to assess historical trends in hydrological drought at regional scale (Section 11.9). Increasing (MED; *high confidence*; WAF, EAS, SALL; *medium confidence*) and decreasing (NEU, SES; *medium confidence*) trends in hydrological droughts have only been observed in a few regions.

#### AR6 on Attribution (p.1577)

There are only two AR6 regions in which there is at least *medium confidence* that human-induced climate change has contributed to changes in meteorological droughts (Section 11.9). In South-western South America (SSW), there is *medium confidence* that human-induced climate change has contributed to an increase in meteorological droughts (Boitier et al., 2016; Garreaud et al., 2020), while in Northern Europe (NEU), there is *medium confidence* that it has contributed to a decrease in meteorological droughts (Gudmundsson and Senewiratne, 2016) (Section 11.9). In other AR6 regions, there is inconclusive evidence in the attribution of long-term trends, but a human contribution to single meteorological events or subregional trends has been identified in some instances. In North America, the human influence on precipitation deficits is complex (Wehner et al., 2017), with low confidence in the attribution of long-term changes in meteorological drought in AR6 regions.

As shown in Figure 8.7.3-96B.1, US long term data (NOAA) shows an insignificantly declining tendency toward extreme dryness (-0.001% per year)

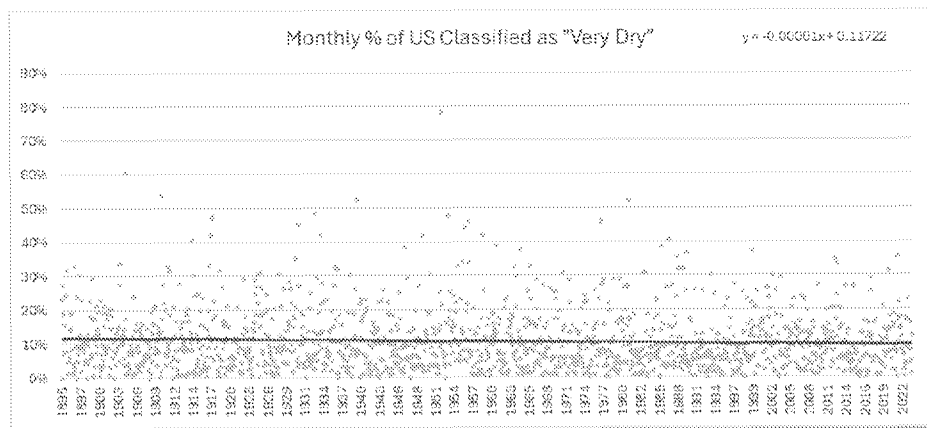


Figure 8.7.3-96B.1: US dryness (%) 1895–2023. Source: NOAA [HYPERLINK "<https://www.ncei.noaa.gov/access/monitoring/uspa/wet-dry/0/>"]

Kogan et al. (2020) examines a 38-year high-resolution satellite-based drought measure and concludes that global drought has not intensified and is not connected to climate change: "it is possible to state firmly that global and main grain countries' drought area and intensity trends have not been following global climate warmings since 1980's."

## 8.32 Extreme weather trends at global and continental indicators of scale extreme weather trends

### 8.32.1 Tropical Cyclones (TCs)

Hurricane strength records for the North Atlantic and the Western Pacific go back to 1850 and the record does not show an increase in either total or major TCs. Figure 8.3.1 was published by Roger Pielke Jr. as an update to the Best Track data series originally presented in Weinko et al. (2012).

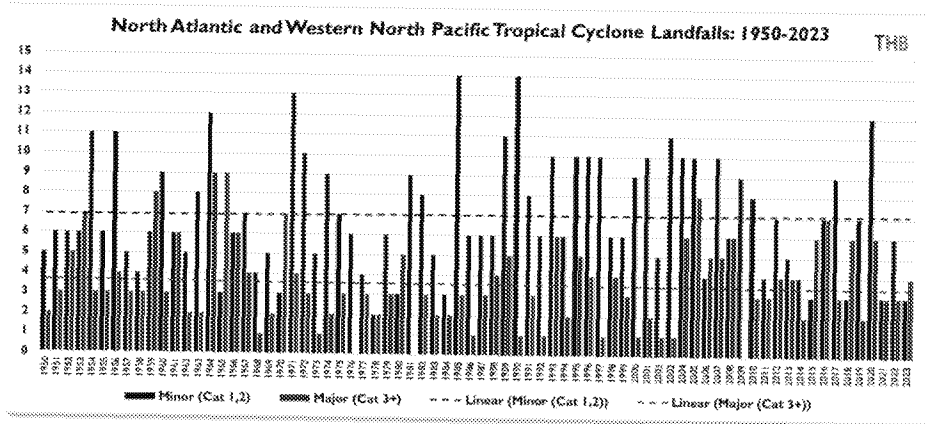


Figure 8.3.1. Tropical Cyclone Landfalls. Source: [HYPERLINK "https://rogerpielkejr.substack.com/p/global-tropical-cyclones"], Weinko et al. (2012)

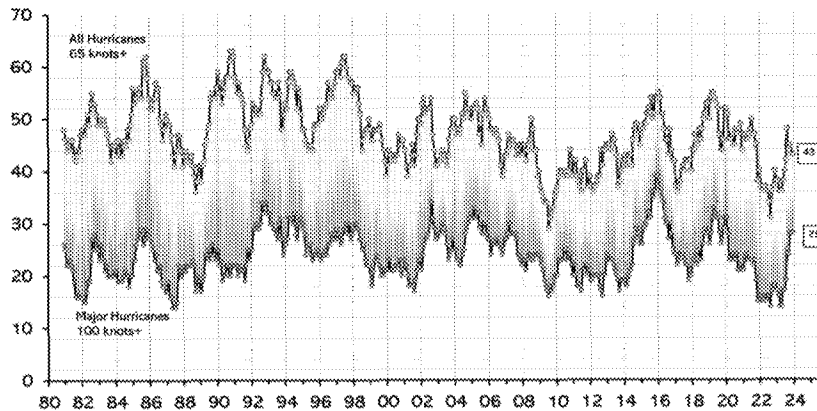
Similarly, after 1980, as shown in Figure 8.3.2, (Maue 2025, [HYPERLINK "https://climatlas.com/tropical/"]) shows that, which reproduces data from the Climate Atlas of Dr. Ryan Maue both the total number of hurricanes and the frequency of major ones hurricanes have not become more common since 1980, the period of rapidly growing human influences. In fact, both numbers have trended down slightly since the 1990s:

Commented [A8]: Climate Atlas of Dr. Ryan Maue

Global Major Hurricane Frequency – 12 month running sums – @RyanMaue

Updated December 31, 2023

Last 30-years: 45.7 H | 24.4 M



Global Major Hurricane Frequency – 12 month running sums – @RyanMaue

Updated March 10, 2025

Last 30-years, annual: 45 H | 24 M

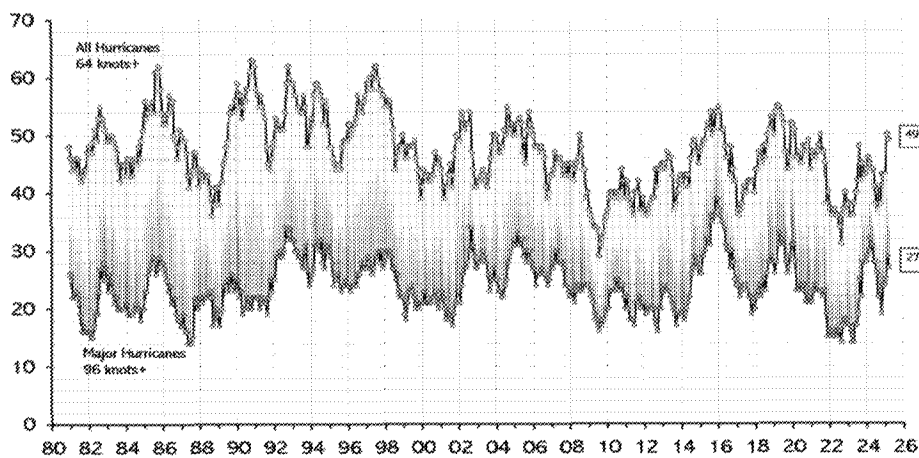


Figure 8.2.2: Global hurricane frequency. Source: Maue (2024/2025)

A metric that combines the number, duration, and frequency strength of TCs is the Accumulated Cyclone Energy (or ACE) Index maintained at Colorado State University, shown in Figure 8.2.3. As is clear, it is also not clearly shows no long-term increase, in fact declining slightly and since 1990 has declined slightly.

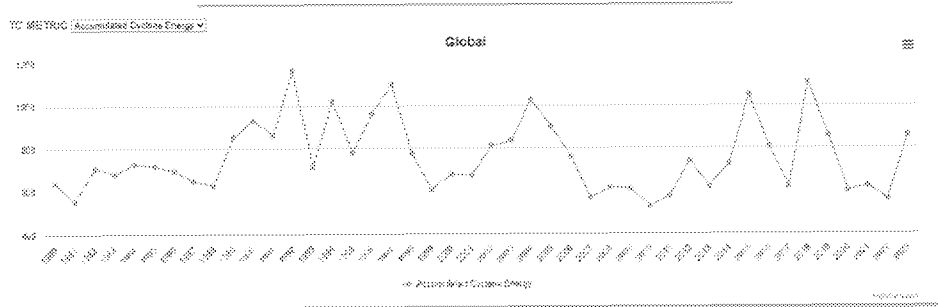


Figure 8.3.3: Global Accumulated Cyclone Energy. Source: Klotzbach (2025)

[HYPERLINK "<https://tropical.atmos.colostate.edu/Realtime/index.php?arch&loc=global>"]

Note that Tu et al. (2024) report that the Power Dissipation Index (PDI), another different measure of the destructiveness of hurricanes that combines hurricane number, duration, and strength, has either remained unchanged or has declined in all global oceanic basins since the mid-1990s. As is clear, it is also not increasing and since 1990 has declined slightly.

Today's global climate simulations are too coarse to project changes in TCs directly. Rather, projections are derived from finer "downscaled" simulations or proxies involving sea surface temperatures, winds, and aerosols. By these methods, a warming climate is expected to show climate models project declining hurricane formation rates, in a warming climate (Chand et al. 2022). Climate models also project fewer Tropical Cyclones under future global warming, and even though models project they will increase in strength, the annual averages of rainfall maxima decline (Stensfield et al. 2020). Note that Tu et al. (2024) report that the Power Dissipation Index (PDI), a measure of the destructiveness of hurricanes, has either remained unchanged or has declined in all global oceanic basins since the mid-1990s.

### 8.7.22.272 Wildfires

The IPCC has not provided an assessment of wildfires.

As shown in Figures 8.7.3.479.1 and 8.3.5 global wildfire activity as measured by European Space Agency peaked over a decade ago and shows a downward trend since then in the 21<sup>st</sup> century.

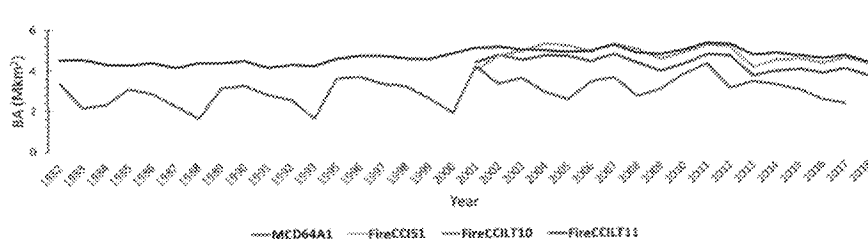


Figure 8.3.4: Global wildfire 1982-2018. Source: Copied from Oton et al. (2021). Note: the different coloured lines represent different data products based on satellites and algorithms used.

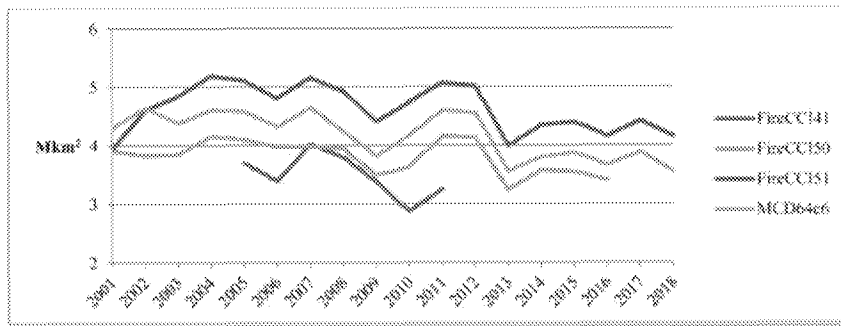


Figure 8.3.5: Global wildfire 2001-2018. Source: Copied from Lizundia-Loiola et al. (2021). Note: the different coloured lines represent different data products based on satellites and algorithms used.

US data from the National Interagency Fire Centre (NIFC) from 1926 to 2023 are shown in Figure 8.3.6.

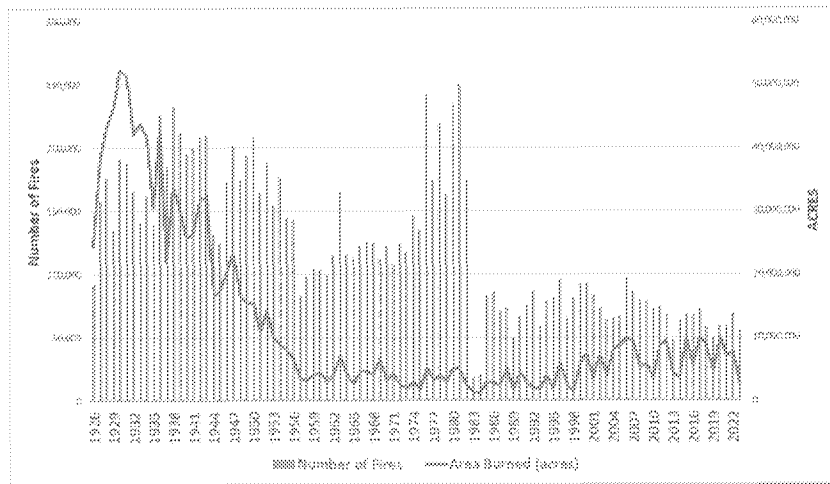


Figure 8.3.6: US wildfires 1926 to 2023. Source: National InterAgency Fire Centre data Pre-2017 [archived]

[<file:///C:/Users/Porter%20Hill/Dropbox/Brucehaven/Projects/DoE/Ross%20drafts/Pre-2017/US%20Wildfires%201926-2017.pdf>] HYPERLINK

Commented [A9]: I thought the trends were due to declining fires in the Amazon, masking any climate-related trend?

Commented [A10R9]: "global area burned appears to have overall declined over past decades, and there is increasing evidence that there is less fire in the global landscape today than centuries ago." Doerr and Santin, Proc Royal Society 2016

2017):%20https:\\web.archive.org\\web\\20200212033452\\https:\\www.nifc.gov\\fireInfo\\fireInfo\_stats\_totalFires.html" ]. 2018-2023: [ HYPERLINK "https://www.nifc.gov/fire-information/statistics/wildfires"]

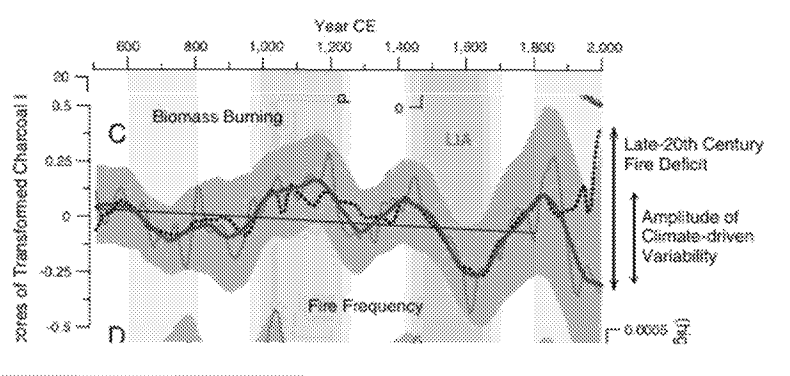
Note that the NIFC has removed the pre-1960 data from its current website. They claim it is because measurement methods changed after 1960. This explanation seems inadequate since agencies blend temperature and extreme weather data series in other contexts when measurement systems changed. ~~in this case if anything,~~ The measurement of wildfires has improved since the early 20<sup>th</sup> century, so any bias will be towards understating early wildfire counts. Nonetheless just focusing on the post-1985 interval the number of fires is not increasing. The area burned did increase but only until about 2007.

Forest fires have always been a part of nature, and they can certainly create conditions that are inhospitable in the short term for all life including humans. Science has confirmed the overall benefit and necessity of the occurrence of forest fires. While recent high-profile fires and seasons serve as a reminder of the potential destructive impact, the highest profile forest fire remains the 1910 Big Blowup fire which destroyed over three million acres including the elimination of entire towns like Taft, MT (Apple 2020). The 1910 fire reshaped the U.S. Forest Service (National Forest Foundation 2022) leading to a focus on fire suppression with a primary goal to defeat all forest fires (Forest History Society 2022). This led to the 10 am rule in 1935 that meant all fires spotted on any day had to be controlled by the following day at 10 am (National Forest Foundation 2022).

While defeating fire is certainly a noble goal, questions began to arise as to whether this behavior "followed the science" (US Forest Service 2022). Over time the U.S. Forest Service has begun to rethink its behavior, recognizing that new approaches such as prescribed burns, fuel elimination and controlled wildfires are more appropriate (Sommer 2016). Recent research is validating this approach and recognizing that more frequent smaller fires in forests likely result in the most healthy forests, water ecosystems and biodiversity (Stephens et al. 2021).

It is difficult to establish a natural baseline for wildfire activity because of active fire suppression activity since 1900. Paleoclimatic evidence indicates, however, that past wildfire activity was much higher than at present. Marlon et al. (2012) used sedimentary charcoal layers to reconstruct fire history of western US for the past 1400 years. They also fit a model to predict expected fire activity as a function of climatic conditions. The results are summarized in Figure ~~8.7.4.2.3~~ 3 below (from Figure 2 in their paper).



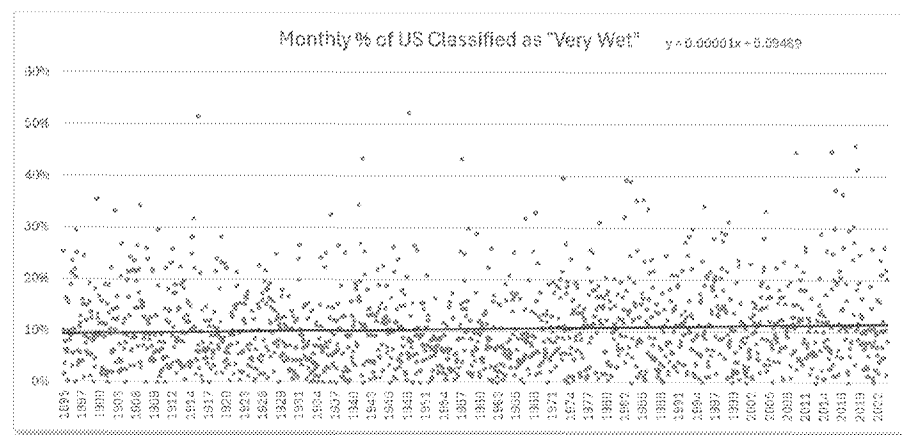


**Figure 8.2.37. Fire frequency and fire deficit in the US.** Source: Copied from Marlon et al. (2012)

In their figure the red line shows the smoothed charcoal record and the black dotted line shows the predicted charcoal record based on the statistical model. The gap at the end implies there has been a growing wildfire deficit over the 20<sup>th</sup> century. In other words, however much fire was observed in the 20<sup>th</sup> century it was less than what would have been observed in previous centuries based on the climatic conditions. Parks et al. (2025) likewise find that despite the recent increase in wildfire burn area in North America, a significant wildfire deficit remains relative to historical wildfire regimes there remains a significant wildfire deficit.

### 8.2.3.3 Precipitation

Figure 8.2.8 shows that US long term data from NOAA shows an insignificantly increasing tendency toward extreme wetness (+0.0001% per year)



**Figure 8.2.8. Long term US wetness (%)** Source: NOAA [HYPERLINK "<https://www.ncei.noaa.gov/access/monitoring/uspa/wet-dry/0>"]

Precipitation will be discussed further in the review of CONUS data below.

#### 8.23.4 Drought

As shown in Figure 8.3.9 US long term data (NOAA) shows an insignificantly declining tendency toward extreme dryness (-0.001% per year)

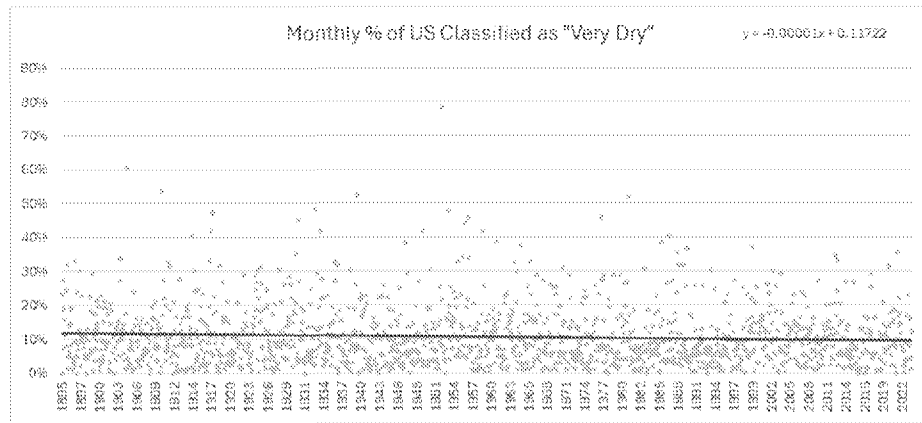


Figure 8.3.9: US dryness (%) 1995-2023. Source: NOAA [HYPERLINK "https://www.ncei.noaa.gov/access/monitoring/uspa/wet-dry/0"]

Kogan et al. (2020) examines a 30 year high resolution satellite-based drought measure and concludes that global drought has not intensified and is not connected to climate change. "It is possible to state firmly that global and main grain countries' drought areas and intensity trends have not been following global climate warming since 1980's."

#### 8.3.4 Analysis of Temperature and precipitation extremes in the Conterminous Contiguous US (CONUS) data on temperature and precipitation extremes

##### 8.34.1 CONUS daily temperatures are becoming less extreme

Daily maximum temperatures in the warm season (TMax, May-Sep) and daily minimum temperatures in the cold season (TMin, Dec-Mar) are available beginning in Dec-1898 (126 years). (The dataset consists of 1,211 CONUS stations designated as United States Historical Climate Network or USHCN stations (Quinlan et al. 1987, Karl et al. 1990). These stations were selected by NOAA as having the fewest problematic issues with gaps, station moves and instrument changes. Where gaps still exist, nearby stations (bias-corrected) were merged so that the median volume of data available for a station is 98%. Although there are certainly errors certainly reside in the dataset, with over

**Commented [A11]:** Again, I think we need a map of where the stations are; something like this one:  
[HYPERLINK "https://www.researchgate.net/publication/258660497\_Uncertainties\_Trends\_and\_Hottest\_and\_Coldest\_Years\_of\_US\_Surface\_Air\_Temperature\_since\_1895\_An\_Update\_Based\_on\_the\_USHCN\_V2\_TOB\_Data/figures?to=1"]  
More importantly, it needs to show how you've cut them up into regions

1,000 stations we can have relatively high confidence in any underlying signal we that might be discovered, can be characterized by relatively high confidence.

We begin with the question of whether the occurrence of daily record high or low temperatures changed has changed since Dec 1898. Each warm season has 153 days (1 May to 30 Sep) and each cold season has 123 days (1 Dec to 31 Mar). For each station and day we calculated the year in which the record highest (lowest) temperature occurred. With 126 years of observations, if there were no temperature trends over time, the expected number of records for TMax would be 1.21 ( $=153/126$ ) per station per year and for TMin 0.96 ( $=123/126$ ) per station per year. Figure 8.4.14 indicates the observed distribution in time of the occurrence of these extreme events.

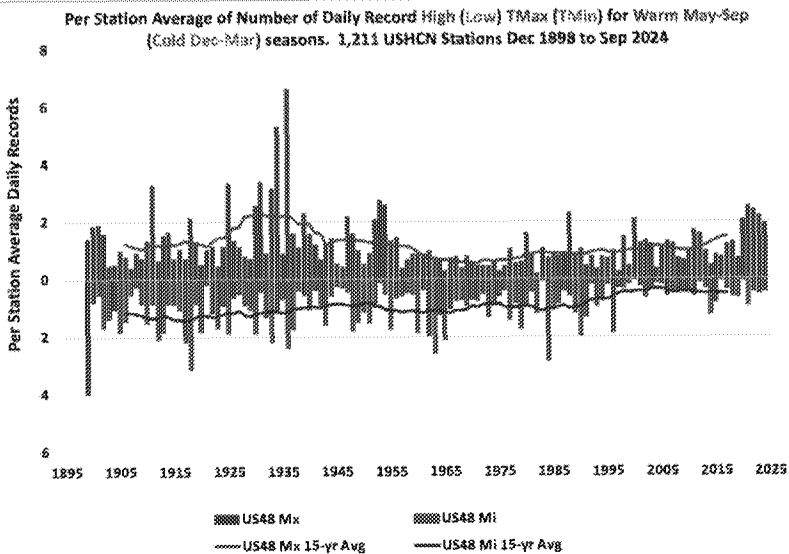
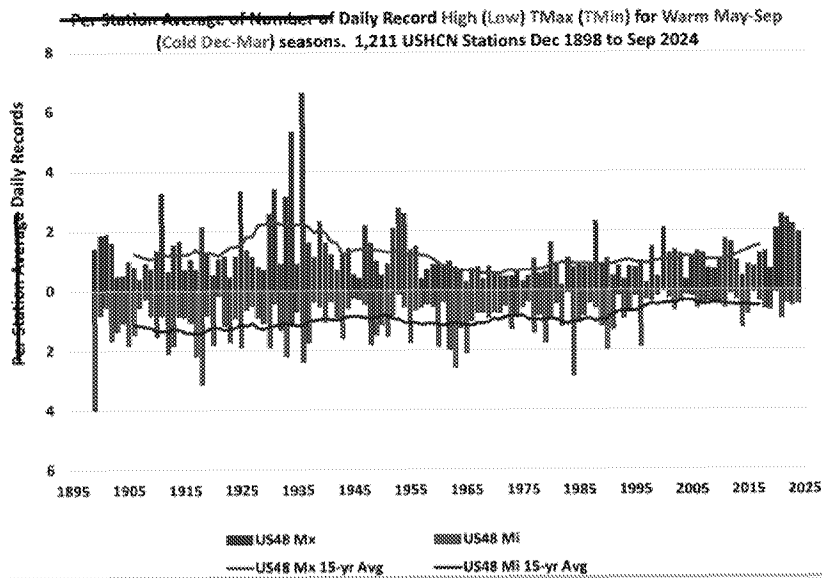


Figure 8.1.110 Number of daily record High (red) and Low (blue) for warm and cold seasons in the CONUS. The lines represent the 15-year running, centered average. Source: 1,211 USHCN stations supplemented as needed to achieve a minimum of 92% of observations in the 126-year period since Dec 1898.

The results indicate a common feature in many metrics of warm-season extremes in the CONUS—the exceptional heat of the 1920s and especially the 1930s, peaking in 1936. On a per-station average, 60% of the TMax records and 59% of the TMin records occurred in the first half of the period (1899–1961).

On the cold side, the Valentine's Day Arctic outbreak in Feb. 1899 stands as the most extensive cold extreme experienced by the CONUS, with 1917–24. The frequency of cold records has declined, especially over the last quarter of the period in which only 13% of the extreme cold events were measured. In contrast, 35% of the extreme TMax records were achieved in the last quarter in accordance with statistical expectations. These general features have been noted in past assessments (IPCC AR5, IPCC AR6, NCA4, NCA5). Combining the two records the overall reduction in numbers of both cold and hot extremes over the past century indicates a climate less prone to extremes.

This pattern is also shown in Figure 8.4.2.1.1. For each station and for each year the hottest warm season and coldest cold season temperatures were calculated and converted to anomalies relative to the station's long-term warm and cold season (respectively) averages. Then the differences between these were computed by station and geographically averaged over all stations, thus yielding an annual measure of the expected range of local extreme temperatures for each year. Figure 8.1.1 shows the 15-year trailing average of this measure which has clearly declined over the past century.

**Commented [A12]:** Does this include a correction for varying station density? If not, it should just read "averaged".

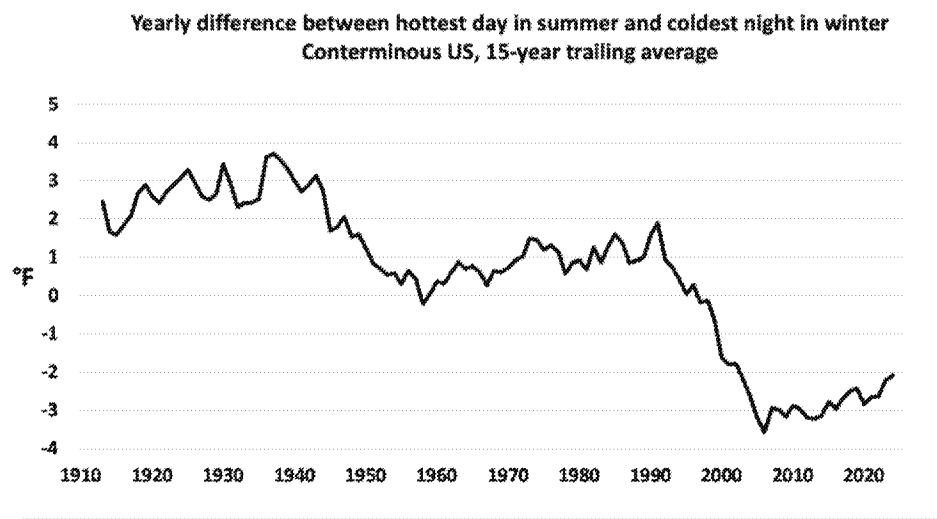


Figure 8.4.2.1.1—15-year trailing average of the difference each year of each station's hottest warm season TMax and coldest cold season TMin relative to the long-term average.

The average difference for each station between the hottest summer TMax and coldest winter TMin has declined about 5°F in the past 126 years. The decline is due mostly to warming winter TMin, but

a decline in the magnitude of summer TMax is also a factor. The rise in TMin has been strongly related to the growing presence of manufactured surfaces around the weather stations over the last 100+ years (Spencer et al. 2025).

Summarizing Figures 8.10.4.1 and 8.4.2.1, while temperature extremes are regularly experienced in the US and attract a great deal of media attention, long-term records show the US climate has become less extreme over time (milder), when measured in terms of the range between warm-season maxima and cold-season minima.

#### 8.34.2 Exceedances of a heat threshold

Under the heading of "The Risk of Temperature Extremes is Changing", the most recent US National Climate Assessment report (NCA5) notes the increase in a threshold metric of number of days at or above 95°F, stating:

*"The western US has been particularly affected by extreme heat since the 1990s, experiencing a larger increase in days over 95°F, as would be expected given the greater warming in that region relative to the eastern US. Several major heatwaves have affected the US since 2018, including a record-shattering event in the Pacific Northwest in 2021."*

Are the occurrences of 95°F days changing? In a climate as varied as that of CONUS, threshold statistics can be misleading. A region with many stations which ~~that~~ have near 95°F TMax average temperatures in the summer might see large swings in the metric when only small changes in average temperatures occur. Elsewhere with stations that either rarely or virtually always achieve 95°F TMax temperatures, a small change will not impact the results much at all. In the past 126 years, the average CONUS station experienced 129 days exceeding 95°C per 6-yr period, but the regional values range from 278 in the Southern Plains to 9 in the Northeast. Thus, one needs to view such threshold analyses with caution.

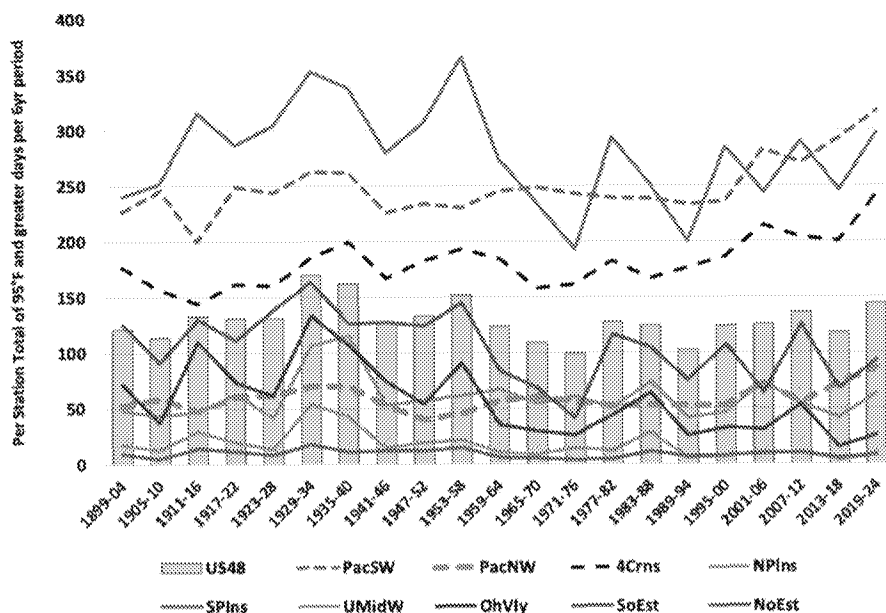


Figure 8.12.4.3. Total number of days  $\geq 95^{\circ}\text{F}$  in 6-yr periods, US 48 (bars) and regions (lines).

In Fig. 8.12.4.3, we see that only three of the nine regions, all in the West, have experienced upward trends in the number of  $95^{\circ}\text{F}$  or hotter days (dashed lines). The CONUS as a whole has not and the other six regions have experienced declines.

The Pacific NW heatwave of 2021 is referenced as supportive information for of the NCA5 claim: an event we examined more closely in Section 6.4. The evidence indicates it was a “black swan” event, i.e., a single, unprecedented event in the existing record, not part of a suggesting it is not indicative of a pattern of increasing extreme heat. For example, the 5-day average tropospheric grid-point temperature anomaly over the Pacific NW during that event was  $+10.8^{\circ}\text{C}$ , the most extreme NH grid-point summer anomaly in the 46 years from over 4 million grids. In contrast, the global anomaly during that time was virtually zero ( $+0.03^{\circ}\text{C}$ , Mads et al. 2024).

The heading “The Risk of Temperature Extremes is Changing” suggests positive trends are now being observed in threshold temperatures on a widespread basis, but that is not evidenced in the combined CONUS results of the figures above.

### 8.34.3 Heatwaves

Heatwaves (consecutive days that exceed an extreme threshold) have a greater societal impact than Of more impact than a single daily record. We measure is the phenomena of heatwaves, or consecutive days which exceed an extreme threshold. For this study, the metric will be the number of “Heatwave Days” here defined as the sum count of all days in May-Sep each year which that exceed

the 90<sup>th</sup> percentile and that occur lie within consecutive periods a run of at least six consecutive days in length. This is equivalent to the method used in NCA5 except that the reference period here is the entire record 1899-2024 while NCA5 limited truncated the reference period to 1961-1990, a cool episode finale. By selecting 1961-1990, the final truncation occurrence of heat positive results (days exceeding the 90<sup>th</sup> percentile) will be enhanced in periods warmer than the reference base period, especially if starting in 1960 and moving to the present (see *Urban Influences* below).

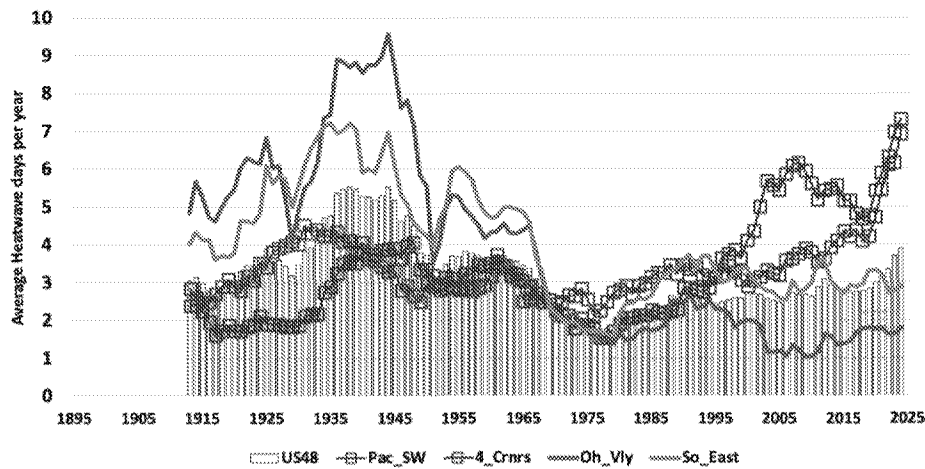


Figure 8.13 4-15-year trailing average of number of heatwave days per year per station in the CONUS (bare) and four regions: Pac\_SW (purple squares, CA, NV), 4\_Cnrs (red squares, AZ, NM, UT, CO), Oh\_Vly (blue, MO, IL, KY, TN, IN, OH, WV) and So\_East (green, MS, AL, GA, FL, SC, NC, VA).

Figure 8.13.4.4 indicates again the excessive heat of the first half of the 20<sup>th</sup> century, primarily in the eastern two-thirds of the nation, as seen in the regional values for the Ohio Valley and the Southeast as examples. The West has seen a recent increase of heatwave days and the two regions with the highest number are shown, the Pacific Southwest and the Four Corners (NCA5). This indicates that the background warm season circulation favored heatwaves in the eastern portions of the country in the first half of the 20<sup>th</sup> century, but in the 21<sup>st</sup> century the patterns have favored heatwaves in the West. For CONUS as a whole, heatwaves are no more common today than they were a century ago.

Of interest here is the regional variation of this metric. The four northern regions (Pacific NW, Northern Plains, Upper Midwest, and Northeast) on average experience 15 to 27 heatwave days per 15-year period. In contrast, the five southern regions (Pacific Southwest, 4-Corners, Southern Plains, Ohio Valley and Southeast) see 37 to 54 such days, essentially twice as many. This suggests the summer circulation pattern is more prone to stationary events in the southern regions while transient systems in the northern regions are more common and thus cut short these potentially longer events.

#### Urban influences



The NCA5 directs readers to the website [HYPERLINK "https://www.globalchange.gov/indicators/heat-waves"] (USGCRP 2023) to view the number of urban heatwaves by decade from the 1960s. The figure reveals shows a monotonic increase in each decade from 2 occurrences per year in the 1960s to 6 in the 2020s. The definition of a heatwave is an unusual but practical measure from a human discomfort perspective—a period of at least 2 consecutive days when the minimum apparent minimum temperature (combination of temperature and humidity) exceeds the 85<sup>th</sup> percentile. Note too, the dataset is limited to the 50 largest U.S. cities in the US.

These increasing values since 1960 presented in USGCRP (2023) are entirely reasonable, but are unrelated to GHG emissions for at least two reasons unrelated to GHG emissions. Urbanization in these cities is a major factor in the rise of TMin relative to co-located TMax and relative to TMin at rural stations. Also, the 1960s was the coldest decade and 1970s the second coldest decade since the 1910's, so this starting date preconditions the time series to show increases. This does not dismiss the real rise in nighttime temperatures in major U.S. cities and the societal impacts associated with these changes. However, we note for a variety of reasons, that summer TMax (especially in rural areas) serves as better response variable for detecting potential changes in heatwaves influenced by changes in the background climate due, for example, to increasing GHGs (Christy et al. 2009). For the CONUS as a whole, the evidence in this section suggests GHG emissions have had little to no effect on heatwaves in the CONUS.

#### 8.3.4.4 Extremes in daily precipitation.

Because precipitation involves a discrete phase change (water vapor to liquid), it is due to its stochastic and episodic in character and therefore precipitation requires careful statistical treatment to understand variability over long time periods (see 8.1 Introduction). The US National Climate Assessments (NCA4, NCA5) have highlighted an increase in the occurrence of the heaviest precipitation events (defined in different ways) primarily in the eastern half of the CONUS, especially the Northeast, when starting in either 1901 or 1958. Interestingly, the regional variations indicate that the largest increases in extreme events are in the Northeast and least the smallest in the West, which is a trend counter to the changes in temperature extremes shown above.

Commented [A13]: Stochasticity and LTP are really different things, but we somehow conflate them in this sentence. Or am I missing something?

Commented [A14R13]: By removing the 'therefore' I think we are now not conflating them.

McKrick and Christy (2019) examined long-term and consistent station observations of daily precipitation to test some of these NCA claims for the Southeast and West Coast. In neither case when the time series were extended back in time (as far as 1872 in some cases) or when starting later (1978), there were no were the trends significant trends for either region. For this report we updated these findings with similarly constructed observations from 20 stations on the Pacific Coast (1938 from San Diego, CA to Blaine, WA, see Figure 8.14), 24 stations in the humid Southeast (1972 from Austin, TX to Washington, DC, see Figure 8.15), and 21 stations in the Northeast (1888 from Buffalo, NY to Gardiner, ME, see Figure 8.16). The results were as follows:

##### Pacific region:

- .....Average precipitation trend is significant (downwards) in Astoria, insignificant elsewhere.
- .....The trend in rainfall variance is positive and significant in Big Sur, insignificant elsewhere.
- .....The trend in daily maximum precipitation is positive and significant in Aberdeen and Big Sur and negative and significant in Newport (insignificant elsewhere).
- .....Averaged over all stations in the region none of these three trend parameters is statistically significant.

##### Southeast region:

- The trend in average precipitation is positive and significant in Mobile and Quitoan, insignificant elsewhere.
- The trend in rainfall variance is positive and significant in Mobile, insignificant elsewhere.
- The trend in daily maximum precipitation is positive and significant in Vicksburg and Norfolk, insignificant elsewhere.
- Averaged over all stations in the region none of these three trend parameters is statistically significant.

#### Northeast region:

- The trend in average precipitation is positive and significant in 9 of 21 locations and in the region averaged overall.
- The trend in rainfall variance is positive and significant in Portland, Albany and Buffalo, insignificant elsewhere.
- The trend in daily maximum precipitation is positive and significant in Portland and Gardiner, insignificant elsewhere.
- Averaged over all stations in the region the trend parameters for variance and maximum precipitation are not statistically significant.

In the Pacific region, over the whole sample, the trend in average precipitation trends downward, being significant only is negative and significant in Astoria, and insignificant elsewhere. The trend in rainfall variance increases, is positive and significant only in Big Sur, and insignificant elsewhere. The trend in daily maximum precipitation is positive and significant in Aberdeen and Big Sur and negative and significant in Newport and insignificant elsewhere. Averaged over all stations in the region none of these three trend parameters is statistically significant.

In the Southeast region over the whole sample the trend in average precipitation is positive and significant only in Mobile and Quitoan, the trend in rainfall variance is positive and significant only in Mobile and the trend in daily maximum precipitation is positive and significant only in Vicksburg and Norfolk. Averaged over all stations in the region none of these three trend parameters is statistically significant.

The Northeast region exhibits a pattern of increasing average rainfall. The trend in average precipitation is positive and significant in 9 of 21 locations and in the region averaged overall. The trend in rainfall variance is positive and significant only in Portland, Albany and Buffalo and insignificant elsewhere and not in the regional average. The trend in daily maximum precipitation is positive and significant only in Portland ME and Gardiner ME and insignificant elsewhere and not in the regional average.

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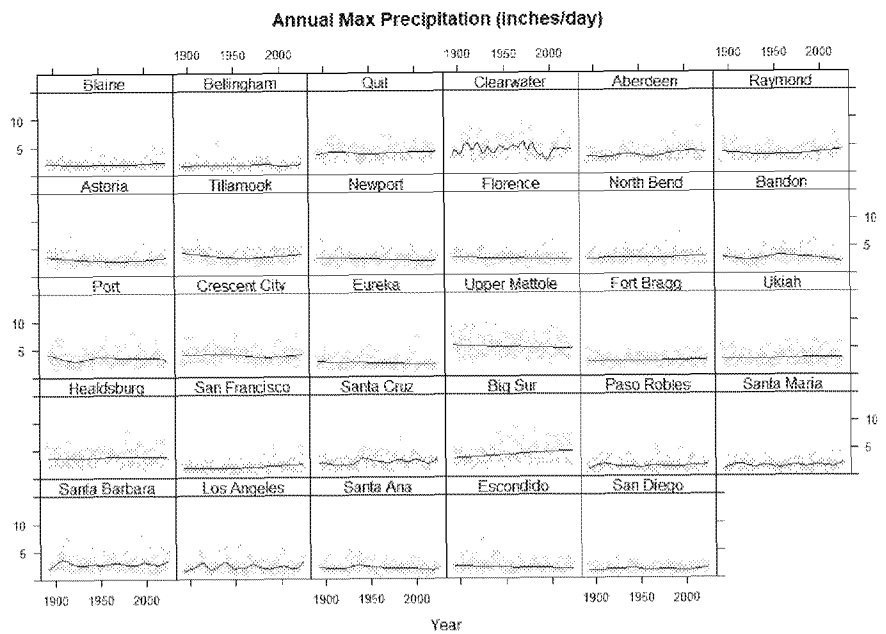


Figure 9.1.1 Annual maximum precipitation for 25 Pacific stations 1950 to present

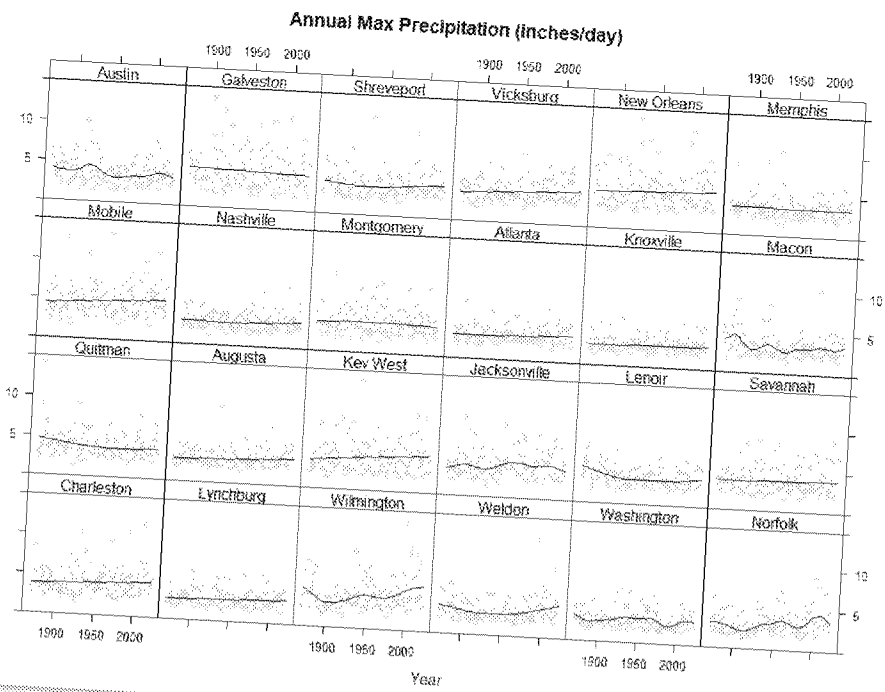


Figure 8.12 Annual maximum precipitation for 24 Southeast stations 1972 to present

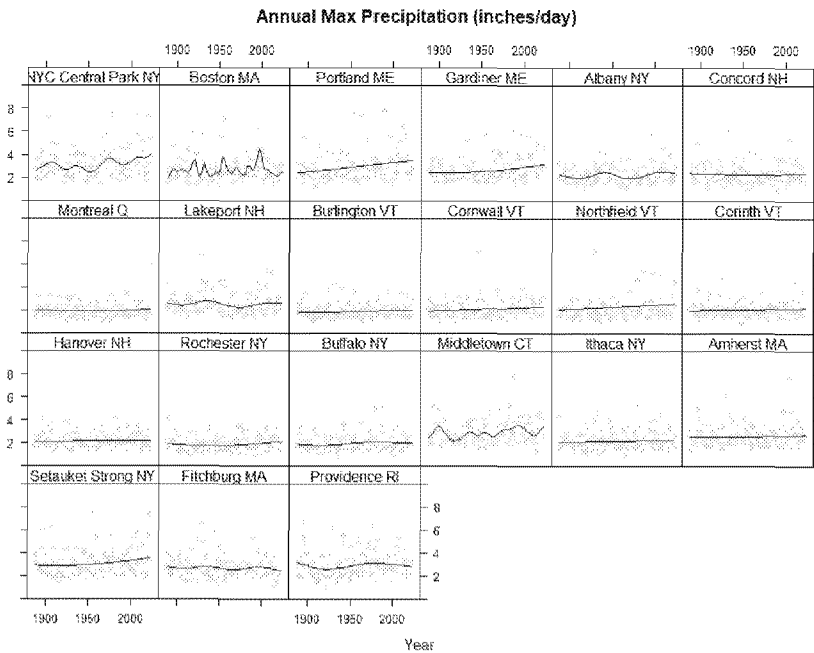


Figure 8.13 Annual maximum precipitation for 21 Northeast stations 1898 to present

#### Pacific Coast heavy rainfall events

The Pacific Coast receives considerable amounts of precipitation from Atmospheric River (AR) events which often last more than a day or two (e.g., Gershunov et al. 2017, Pan et al. 2024). The worst known such event in recent history was the ArkStorm that occurred between December 1861 and January 1862, which dumped nearly 10 feet of rain in parts of California and submerged the entire Central Valley for weeks under as much as 15 feet of water (Brewer 1930, Nall and Halbert 2007). Paleoclimate research has found six megastorms more severe than 1861–1862 in California during the last 1000 years, occurring at intervals of 300 years or so (Porter et al. 2011).

#### SIDEBAR: Perils of short data records

San Francisco provides a good case study of the limitation of using short historical samples to characterize natural variability of extreme events. Suppose we use a 130-year sample of daily San Francisco precipitation from 1895 to 2024 and we look for 3-day, 5-day, 14-day and 30-day rainfall records. The results are as shown in Table 8.12.

| Event  | Record (inches) | Year |
|--------|-----------------|------|
| 3-day  | 6.94            | 2023 |
| 5-day  | 6.55            | 2023 |
| 14-day | 12.62           | 2023 |

30-day 1893 1998  
Table 8.12: Extreme rainfall records, San Francisco, 1893-2024.

The records all cluster in the more recent data. 2023 appears to be an exceptional year and since it is near the end of the sample it would might point to the possibility suggest that the climate has shifted into a potentially more hazardous state, perhaps as a result of human influences.

But the picture is very different if we use a sample that begins 115 years earlier, in 1850. If we extend the record back to 1850 the picture changes. Table 8.2.3 shows that the record-setting events then all happened in the 1860s. Furthermore 2023 is now not even in 2<sup>nd</sup> place but falls to 3<sup>rd</sup> or 4<sup>th</sup>. Also, comparing the records of the two charts the extreme precipitation events in 1862 and 1867 involved considerably more rainfall than the 1995 and 2023 events, with 14- and 30-day totals about 50 percent higher.

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| Event  | Record (inches) | Year | Rank of 130-yr extreme |
|--------|-----------------|------|------------------------|
| 3-day  | 8.85            | 1867 | 3                      |
| 5-day  | 9.80            | 1867 | 3                      |
| 14-day | 19.05           | 1862 | 4                      |
| 30-day | 28.25           | 1862 | 2                      |

Table 8.23: Extreme rainfall records, San Francisco, 1850-2024.

The The characterization of the range of natural variability is made even more remarkable when paleoclimate evidence is examined. Porter et al. (2011) discovered that in the past 1,800 years at least six megastorms were more intense than the devastating 1861-62 Arktstorm that struck the region. Thus, evidently, such extreme events have impacted the region about every 300 years, though not since 1895.

This example illustrates the limitations of using relatively short climate periods (~130 years) to assess the character and range of natural variability in general and of extreme events in particular. Accurate representation of the full range of natural variability is necessary for any attribution analyses (see 6.4). Infrastructure planners, emergency management institutions and attribution scientists would understand the significant mischaracterization of the magnitude of a future extreme if based only on the last 130 years. In this case, a single time sample of 130 years provides an underestimation of the extreme value by up to 50% determined when adding only 45 more years of observations. Compared to millennial-scale paleoclimate evidence, an even greater underestimation would occur. An important lesson is that the climate can deliver great surprises on its own even without human influences.

We examine occurrences of 5-day deluges as follows. In a 130-year span there are 26 5-year intervals. At each location we computed the 5-day precipitation totals throughout the year and selected the 26 highest values. A single year may have more than one of the 26 heaviest. Each of these can be thought of as 1-in-5-yr events. If there are no trends in precipitation then the total number of these events across all stations should be evenly spread out on an annual basis over the years. In Fig. 8.14.4.5 we show the distribution in time of these events. The deluges associated with the massive 1997-98 El Niño event are readily apparent. While erratic, as is typical of these types of precipitation metrics, there is no indication of a tendency to become more frequent over time.

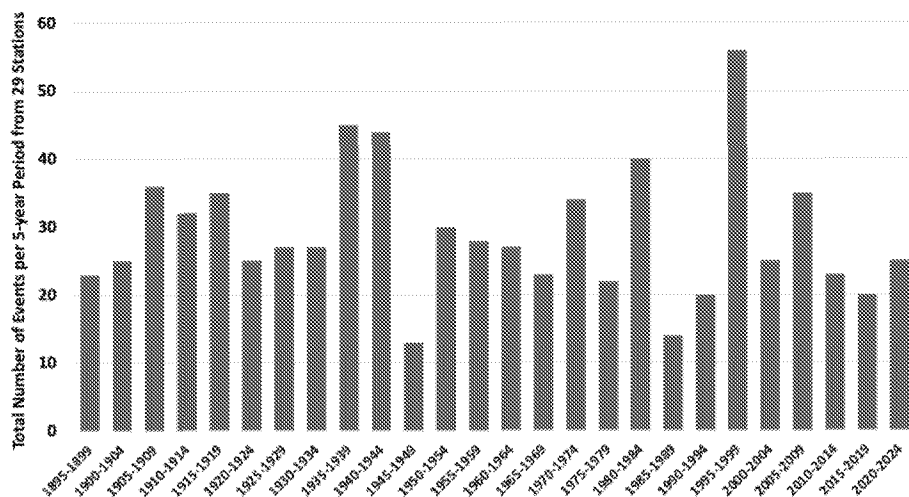


Figure 8.144.5 The time distribution by 5-year periods of the 26 heaviest occurrences for each station (i.e., nominal 1-in-5-year event).

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#### South-east heavy rainfall events

The temporal pattern of 5-day totals of the 1-in-5yr heavy events in the humid Southeast (Figure 8.151.6) is generally unremarkable, though a cluster of higher values appears in 1995 to 2019. The increase in those years is due largely to the 4 northeastern-most stations of Wilmington NC, Weldon NC, Washington DC, and Norfolk VA. This confirms the pattern indicated in NCA4 and NCA5 of a tendency for an increasing frequency of heavy events, due to a temporal clustering of tropical storms from eastern NC to Maine discussed below. Otherwise, the remaining 26 stations show an unremarkable temporal distribution of heavy events.

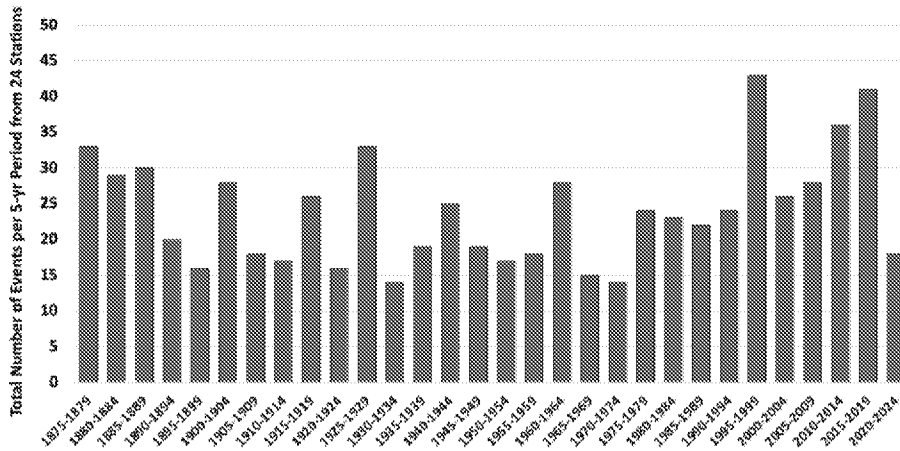


Figure 8.154.6. As above but for the 30 heaviest 1-in-5-yr events for 24 stations in the humid Southeast from Austin, TX to Washington, DC in 5-year bins for 1875-2024.

#### Northwest heavy rainfall events

Fig. 8.16.4.2 shows the 27 (1-in-5-yr) heaviest 3-day events for the last 135 years in 21 stations in the Northeast (including Montreal, Canada). We use 3-day totals here as this produced the largest variations in time. In this region, 72% of the events occur during June to October and are dominated by tropical incursions of hurricanes, tropical storms or tropical storms that transition to extratropical systems. According to NCA4 and NCA5 this region experienced the largest increases in extreme events, so it shall be examined more closely.



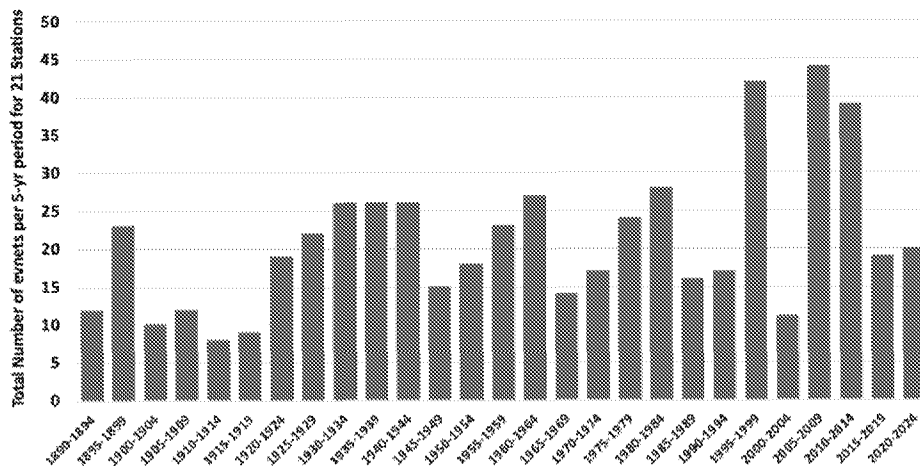


Figure 8.16.4.7. Time distribution of the heaviest 27 (1-in-5-yr) heaviest 3-day precipitation events for 21 stations from NY to ME, including Montreal.

Howarth et al. (2019) report differences in the Northeast between two 18-year periods: 1979-96 and 1997-2014 (a similar region as in Fig. 8.16 that includes PA and NJ) of various precipitation extremes. One metric which indicated a dramatic increase (317%) was found for 24-hr events  $\geq 6$  inches. This high increase is due to the very small numbers of such events of which there were only 6 in the first period and 25 in the second as reported for 58 stations. This high percentage increase is due to the very small numbers of the events; only 6 in the first period and 25 in the second. Most of the stations did not record such an event suggesting these erratic, episodic events over brief 18-yr periods, need scrutiny by additional statistical methods.

Using the information in Fig. 8.16.4.7 over the same years as Howarth et al. we find a 51% increase in the frequency of heavy events between the two periods. One can see in Fig. 8.16 that it was unfortunate that Howarth et al. ended in 2014 prior to a return to the long-term average of such events.

A feature of Howarth et al. is the use of single-day totals which is questionable because extreme events are often spread across the time-of-observation boundary. Thus stations measuring at 0700 LT versus those at Midnight will have differing results for a particular event which would then have major impacts on counting these events. We use the 3-day totals in Fig. 8.16.4.7 to be sure to capture the extent of these extreme downpours. In any case, we can confirm that the period 1997 to 2014 experienced a cluster of heavier events as Howarth et al. have documented.

Howarth's most remarkable claim (317% increase in 6" days) is potentially misleading because it is a threshold statistic (see Section 8.3.4.2 above) and a ratio of small numbers over a short period. The result is not representative of relative extreme events for the whole region since the majority of stations never experienced a 6" total. Fig. 8.16 above determines the same number of events for each station (27 heaviest events) whose heaviest values ranged from 4.4" to 12.5" and their 27<sup>th</sup> heaviest values ranged from 3.3" to 5.0". This analysis thus allows each station to be equally represented. In

other words, if there is a region-wide increase in heavy events, it should be seen in the sum of all stations. Note too that the period of record here is 135 years vs. 36 years of Howarth et al. Except for three 5-year periods between 1995 and 2014 there is nothing statistically remarkable about the results in Fig. 8.164.2.

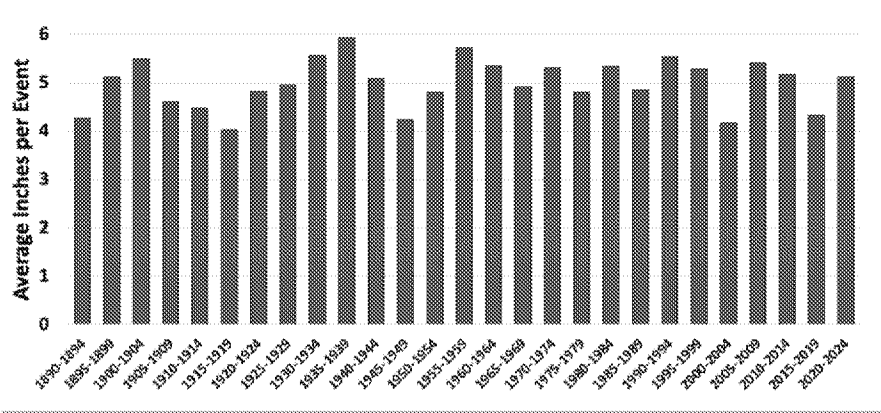


Figure 8.174.8. Average amount of precipitation falling in the 1-in-5yr events for the NE stations.

An interesting aspect of Northeast precipitation is that there has been no change in the amount of precipitation per heaviest event, as shown in Fig. 8.174.8. The trend is only +0.02"/decade. The highest amount, 1935-39, includes the Great New England Hurricane of 1938, one of the rare major (Category 3 or higher) hurricanes to strike the region. The results in Figs. 8.164.5 and 8.164.7 suggest that though there was an uptick in the number of events during the period 1995 to 2014, the events, individually, are not becoming more intense.

Jong et al. (2024) document the increase of tropical influences on precipitation events in the Northeast since 1959 and concluded, "The autumn extreme precipitation trend over the Northeast US is primarily attributed to tropical cyclone-related events since the 1990s." The question then becomes, was the temporal clustering of tropical systems in 1997-2014 which affected the Northeast a response to increasing GHGs? Jong et al. examined CMIP-6 model output which suggests that there will be fewer such systems in the 21<sup>st</sup> century but that the intensity of the rainfall events might increase. This conjecture is not seen in Fig. 8.17 where the amount per event has remained steady over the 135-year period.

For substantial urban areas there is some evidence to indicate the heaviest rainfall events may be redistributed due to the impact urban infrastructure has on the local weather (e.g., Pielke Sr. et al. 2011; Zhang et al. 2018; Yang et al. 2024). Yang et al. state, "Cities that experience compact development tend to witness larger increases in extreme rainfall frequency over downtown than their rural surroundings, while the anomalies in extreme rainfall frequency diminish for cities with

dispersed development." While this is an important insight to consider, the effect on the specific stations used in this analysis is unknown, or at least not detectable in Fig. 8.1.7.

In summary, the evidence from the historical record of extreme precipitation events in the CONUS is generally not consistent from region to region so that inferences regarding trends and their projections are wrought with significant uncertainty. In most regions and perhaps all, it is our opinion that the very nature of the erratic and episodic character of extreme precipitation events renders the discovery of statistically significant changes, including a relationship to CO2 concentrations, a recultyst to be achieved (McKerriek and Christy 2019).

#### 8.7.4.5.10 Summary

To be inserted

Based on the content provided in the document, here are the five most important takeaways:

- Limited Detection of Anthropogenic Signals: The IPCC has asserted high confidence in detecting an anthropogenic signal in only 1 out of 34 weather impact categories, and medium confidence in 4 more. For the remaining 26 categories, no anthropogenic signal is claimed to be detected.
- Slow Emergence of Trends: Even under the most extreme forcing scenario (RCP8.5), the IPCC expects very few anthropogenic trends to emerge within this century for most weather impacts.
- Natural Variability Dominance: Natural variability continues to dominate patterns of extreme weather systems. Simple assertions of trend detection are often complicated by regional heterogeneity and trend reversals over time.
- RCP8.5 Scenario Implausibility: The document notes that the RCP8.5 scenario is described as an implausible high-end storyline, not a "base case" or "business-as-usual" projection.
- Conflicting Messages on Attribution: The document mentions that AR6 (IPCC Sixth Assessment Report) offers conflicting messages about the attribution of extreme weather to anthropogenic causes, highlighting the complexity and uncertainty in this area of climate science.

These takeaways emphasize the nuanced and complex nature of attributing extreme weather events to climate change, and the importance of considering natural variability and uncertainty in climate projections.

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## Appendix: Review of IPCC and NCA Findings on Extreme Weather

The sources we review will be denoted as follows:

**SREX:** The IPCC *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (2012)

**AR5:** The IPCC *Fifth Assessment Report Working Group I* (2013).

**AR6:** The IPCC *Sixth Assessment Report Working Group I* (2021).

**NCA17:** The *US Climate Science Special Report of the Fourth National Climate Assessment* (2017) Volume I Chapter 6.

### 8A.1 Overview: IPCC Assessment of signal emergence in extreme weather types (AR6 WG1 Table 12.12)

Table 8A.1 reproduces the findings of AR6 Table 12.12 which indicates, for 34 major weather event and impact types, whether a signal of anthropogenic forcing has been detected in the historical record (column 1), whether such a signal is likely to emerge by 2050 under the extreme RCP8.5 scenario (column 2) and whether it is likely to emerge by 2100 under RCP8.5 forcing (column 3). It should be borne in mind that the latter two columns suffer from the deficiencies of GCMs discussed in Chapter XX. And as we discussed in Ch. X on attribution, AR6 offers three conflicting messages within the AR6 regarding about attribution of extreme weather. Nevertheless, we provide this Table is provided here for reference.

Several patterns stand out. First, detection of an anthropogenic signal is asserted with *high confidence* in only four out of the 34 weather impact categories an anthropogenic signal is asserted with *high confidence* in only four, and with *medium confidence* in a further four. For the rest, the IPCC does not *NOT* claim to have detected an anthropogenic signal in the remaining 26 categories. Of the four *high confidence* assertions, two are for changes in average temperatures (air and ocean), which hence are not measures of extreme weather. Also two further, two of the four *medium confidence* assertions are related to ocean chemistry and thus are likewise not related to extreme weather. The IPCC does not *NOT* assert a detectable human influence on many non-temperature weather features such as wind, precipitation, flooding, and drought, etc.

Second, as shown in columns 2 and 3 show that the IPCC expects very few such anthropogenic trends signals to emerge within this century, even under the most extreme forcing scenario. As we discuss in Section 4.2 the RCP8.5 scenario is an implausible high-end storyline, it is not a “base case” or “business-as-usual” projection. Yet even still, *even so*, most weather impacts are not expected to exhibit *show* an anthropogenic signal this century. As will be clear from the underlying report text, natural variability dominates patterns of extreme weather systems and simplistic assertions of trend detection are frequently undermined by regional heterogeneity and trends reversals over time.

| Climate Impact Driver Type | Climate Impact Driver Category | Already emerged in the Historical Record <sup>1</sup> | Emerging by 2050 in Most Extreme CO <sub>2</sub> Emission Scenario <sup>2</sup> | Emerging by 2100 in Most Extreme CO <sub>2</sub> Emission Scenario <sup>2</sup> |
|----------------------------|--------------------------------|-------------------------------------------------------|---------------------------------------------------------------------------------|---------------------------------------------------------------------------------|
| Heat & Cold                | Average air temperature        | YES in most regions                                   | YES                                                                             | YES                                                                             |
|                            | More heat extremes             | YES in most regions                                   | YES in land regions                                                             | YES                                                                             |
|                            | Fewer cold extremes            | YES in a few regions                                  | YES in many regions                                                             | YES                                                                             |
|                            | Less frost                     | NO                                                    | NO                                                                              | NO                                                                              |

|              |                                         |                          |                       |                       |
|--------------|-----------------------------------------|--------------------------|-----------------------|-----------------------|
| Water & Drip | Average precipitation (inches per year) | NO                       | YES (less) YES (decr) | YES (less) YES (decr) |
|              | River flooding                          | NO                       | NO                    | NO                    |
|              | Heavy precipitation & rainfall (inches) | NO                       | NO                    | YES in a few regions  |
|              | Landslides                              | NO                       | NO                    | NO                    |
|              | Acidity                                 | NO                       | NO                    | NO                    |
|              | Hydroelectricity                        | NO                       | NO                    | NO                    |
|              | Agricultural & residential drought      | NO                       | NO                    | NO                    |
| Wind         | Fire weather                            | NO                       | NO                    | NO                    |
|              | Average wind speed                      | NO                       | NO                    | NO                    |
|              | Severe wind storm                       | NO                       | NO                    | NO                    |
|              | Tropical cyclone                        | NO                       | NO                    | NO                    |
| Snow and Ice | Snow and dust storm                     | NO                       | NO                    | NO                    |
|              | Severe blizzard & ice storm             | NO                       | YES in a few regions  | YES Arctic snow       |
|              | Permafrost                              | YES                      | YES                   | YES                   |
|              | Lake & river ice                        | NO                       | YES                   | YES                   |
|              | Arctic sea ice                          | YES                      | YES                   | YES                   |
|              | Antarctic sea ice                       | NO                       | YES                   | YES                   |
|              | Heavy snowfall and ice storms           | NO                       | NO                    | NO                    |
|              | Hail                                    | NO                       | NO                    | NO                    |
|              | Snowmelt                                | NO                       | NO                    | NO                    |
|              | Snow cover                              | NO                       | YES                   | YES                   |
| Coastal      | Coastal flood                           | NO                       | NO                    | NO                    |
|              | Coastal erosion                         | NO                       | NO                    | NO                    |
|              | Coastal upwellings                      | YES                      | YES                   | YES                   |
| Open Ocean   | Average ocean temperature               | YES                      | YES                   | YES                   |
|              | Marine biodiversity                     | NO                       | NO                    | NO                    |
|              | Ocean acidity                           | NO                       | YES                   | YES                   |
|              | Ocean salinity                          | YES                      | YES                   | YES                   |
| Other        | Dissolved oxygen                        | YES (Pacific & S. Ocean) | YES                   | YES                   |
|              | Air pollution                           | NO                       | NO                    | NO                    |

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*(RM May 13 edits: Inserted Judy's new Sect 8.3 + wildfire text, John's revised Fig 8.4.2 short text in place of Table 8.2.1.)*  
*(IRC edits May 14: folded the results from the three precipitation extremes from Ross's analysis into each of the already-discussed sections, minor edits)*

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## **78 Extreme weather in the US and elsewhere**

### **78.1 Introduction**

High impact weather extremes, usually related to temperature, and/or precipitation and/or excessive wind, often can disrupt infrastructure and therefore endanger human health and thriveability/wellbeing. Indeed, the ability of any surface-dwelling species to live productively is somewhat constrained by these extremes which in essence create the bounding limits for survival. The issue is not whether extremes occur, for they are intrinsic to the chaotic climate system. Rather, it is whether there are long-term (decadal scale) changes in the frequency and/or character of extremes ("detection"), as well as the extent to which such changes here is whether these extremes, and their attendant changes in potential danger/hazards, may be changing and if so whether the change is in response caused by anthropogenic emissions increases in infrared-absorbing of greenhouse gases (GHGs) ("attribution"), (e.g., IPCC AR6 Seneviratne et al. 2021).

It is naive to assume that any recent unprecedented extreme event observed recently is caused by human influences on the climate. Unfortunately, that's that assumption is wrong in two ways. First, climate is about the statistical properties of weather over decades, not single events. And second, there are only about 130 years of the reliable. Unfortunately, observational records that can be analyzed statistically, extend back only for the sample of time from which we are able to quantitatively analyze variations in extreme events is quite brief, about around 130 years. That brief interval does not. This period certainly does not begin to contain all of the extreme events that the climate system is able to create naturally on its own. Over geologic time the climate system has generated an (essentially) infinite variety of weather patterns and extremes which that humans have never observed, and thus do not enter our are absent from the databases from which used to determine extreme statistics, are determine 4- [see *Perils of short data records* below]. Thus, assuming that a for that reason, attributing climate pattern or an extreme event hitherto unprecedented in the record not experienced in our lifetime must therefore be the result of enhanced GHG concentrations requires the assumptions about the smallness/magnitude of that natural variations, are insignificant.

This is especially true for precipitation events. The hydrological literature has long noted the phenomenon of *Long-Term Persistence* (LTP) in rainfall data (Hurst 1951, Cohn and Lins 2005, Markonis and Koutsoyiannis 2015). LTP has a formal mathematical definition but it can be thought of intuitively as the presence of natural variations with strong autocorrelation properties that result in cycle-like behavior on long time scales. The presence of LTP requires very-long data samples/records to obtain accurately accurate estimates of variance/variability. Analysis of analysis of data samples that are records short relative to the LTP scale will tend to yield underestimates variability, therefore underestimated variances which in turn yields overstating the significance of apparent trends and underestimation/underestimating of the likelihood of extreme events (Cohn and Lins 2005).

<sup>1</sup> For example, under the simplest statistical assumptions there is a 37 percent chance that a 100-year event is NOT present in a century-long record.

A good example of LTP is the eight-century long record of the annual minimum height of the Nile River observed at Roda Island in Cairo shown below in Figure B7.1.1. Since human influences on the global climate were negligible before the 20<sup>th</sup> century, the century-scale variability of the thirty-year average is entirely natural. Egyptians of the seventh and eight centuries would have been incorrect to assume that the worsening drought during that time was the “new normal.”

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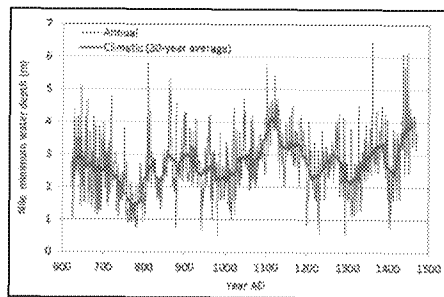


Figure B7.1.1: Nile River discharge [details, source]

With these caveats in mind we examine the evidence for changes in selected weather and climate extremes. A theme that emerges when reviewing this topic is the wide gap between public perceptions and scientific evidence. It has become routine in media discussions, government and private sector discussions and even in some academic literature to make generalized assertions that extreme weather of all types is getting worse due to GHGs and climate change. Yet expert assessments have not typically drawn such sweeping conclusions and instead have emphasized the difficulty both of identifying specific trends and establishing a causal connection with anthropogenic forcing.

In the sections to follow we cite provide excerpts from various IPCC and NCA assessment reports denoting the sources as follows:

For the benefit of readers who may not have read the relevant reports in the Appendix to this chapter we will begin provide with extended excerpts of these findings from previous IPCC and NCA assessments, then in the remainder of this chapter survey additional data relevant to US and global extreme weather trends.

## 8.2 Review of IPCC and NCA Findings on Extreme Weather

The sources we review will be denoted as follows:

*SREX: The IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (2012)*

*AR5: The IPCC Fifth Assessment Report Working Group 1 (2013)*

*AR6: The IPCC Sixth Assessment Report Working Group 1 (2021)*

*NCA17: The US Climate Science Special Report of the Fourth National Climate Assessment (2017) Volume I Chapter 6.*

Note that in the excerpts provided *italics* are in the original whereas **boldface** emphasis is added.

### 8.2.1 OverviewContext: IPCC Assessment of signal emergence in extreme weather types (AR6 WG1 Table 12.12)

This chapter is concerned with detection of trends. Chapter 7 looked at attribution including for extreme weather. Since there is considerable public interest in the question of whether humans are causing trends in extreme weather to get worse it is useful to begin with the summary Table 8.2.1 which reproduces the findings of AR6 Table 12.12 which indicates, for 34 major weather event and impact types, whether a signal of anthropogenic forcing has been detected in the historical record (column 1), whether such a signal is likely to emerge by 2050 under the extreme RCP8.5 scenario (column 2) and whether it is likely to emerge by 2100 under RCP8.5 forcing (column 3). It should be borne in mind that the latter two columns suffer from the deficiencies of GCMs discussed in Chapter XX. And as we discussed in Ch. X7 on attribution, AR6 offers conflicting messages about attribution of extreme weather. Nevertheless, we provide this Table for reference context.

Several patterns stand out. First, detection of an anthropogenic signal is asserted with *high confidence* in only four of the 34 weather impact categories, and with *medium confidence* in a further four. The IPCC does NOT claim to have detected an anthropogenic signal in the remaining 26 categories. Of the four *high confidence* assertions, two are for changes in average temperatures (air and ocean), which are not measures of extreme weather. Further, two of the four *medium confidence* assertions are related to ocean chemistry and are also not related to extreme weather. The IPCC does NOT assert a detectable human influence on many non-temperature weather features such as wind, precipitation, flooding, and drought.

Second, columns 2 and 3 show that the IPCC expects very few anthropogenic trends to emerge within this century, even under the most extreme forcing scenario. As we discuss in Section 4.4, the RCP8.5 scenario is an implausible high-end storyline, not a “base case” or “business-as-usual” projection. Even so, most weather impacts are not expected to show an anthropogenic signal this century. Natural variability dominates patterns of extreme weather systems and simplistic assertions of trend detection are frequently undermined by regional heterogeneity and trend reversals over time.

| Climate Impact Driver Type | Climate Impact Driver Category               | Already emerged in the Historical Record? | Emerging by 2050 in Most Extreme CO <sub>2</sub> Emissions Scenario? | Emerging by 2100 in Most Extreme CO <sub>2</sub> Emissions Scenario? |
|----------------------------|----------------------------------------------|-------------------------------------------|----------------------------------------------------------------------|----------------------------------------------------------------------|
| Heat & Cold                | Average air temperature                      | YES in most regions                       | YES                                                                  | YES                                                                  |
|                            | More heat extremes                           | YES in most regions                       | YES in land regions                                                  | YES                                                                  |
|                            | Fewer cold extremes                          | YES in a few regions                      | YES in many regions                                                  | YES                                                                  |
|                            | Less frost                                   | NO                                        | NO                                                                   | NO                                                                   |
| Wet & Dry                  | Average Precipitation (Increase or Decrease) | NO                                        | YES (inc) YES (dec)                                                  | YES (inc) YES (dec)                                                  |
|                            | River Flooding                               | NO                                        | NO                                                                   | NO                                                                   |
|                            | Heavy rain & rainfall flood                  | NO                                        | NO                                                                   | YES in a few regions                                                 |
|                            | Landslide                                    | NO                                        | NO                                                                   | NO                                                                   |
|                            | Aridity                                      | NO                                        | NO                                                                   | NO                                                                   |
|                            | Hydrologic drought                           | NO                                        | NO                                                                   | NO                                                                   |
|                            | Agricultural & ecological drought            | NO                                        | NO                                                                   | NO                                                                   |
|                            | Fire weather                                 | NO                                        | NO                                                                   | NO                                                                   |
|                            | Average wind speed                           | NO                                        | NO                                                                   | NO                                                                   |
| Wind                       | Strong wind storm                            | NO                                        | NO                                                                   | NO                                                                   |

|              |                                  |                          |                      |                 |
|--------------|----------------------------------|--------------------------|----------------------|-----------------|
|              | Tropical cyclones                | NO                       | NO                   | NO              |
|              | Sand and dust storms             | NO                       | NO                   | NO              |
| Snow and ice | Snow, glacier, & ice sheet       | NO                       | YES in a few regions | YES Arctic snow |
|              | Permafrost                       | YES                      | YES                  | YES             |
|              | Land & river ice                 | NO                       | YES                  | YES             |
|              | Arctic sea ice                   | YES                      | YES                  | YES             |
|              | Antarctic sea ice                | NO                       | YES                  | YES             |
|              | Heavy snowfall and ice storm     | NO                       | NO                   | NO              |
|              | Hail                             | NO                       | NO                   | NO              |
|              | Snow avalanche                   | NO                       | NO                   | NO              |
|              | Relative sea level               | NO                       | YES                  | YES             |
| Coastal      | Coastal flood                    | NO                       | NO                   | NO              |
|              | Coastal erosion                  | NO                       | NO                   | NO              |
|              | Average ocean temperature        | YES                      | YES                  | YES             |
| Open Ocean   | Major heat wave                  | NO                       | NO                   | NO              |
|              | Ocean acidity                    | NO                       | YES                  | YES             |
|              | Ocean salinity                   | YES                      | YES                  | YES             |
|              | Dissolved oxygen                 | YES (Pacific & S. Ocean) | YES                  | YES             |
|              | Air pollution weather            | NO                       | NO                   | NO              |
| Other        | Solar or IR radiation at surface | NO                       | NO                   | NO              |

Table B.3-1. IPCC AR6 summary of the probable emergence of an anthropogenic signal above natural climate variability for all global or regional "climate impact drivers" (CIDs) of concern for humans and ecosystems in response to increasing atmospheric greenhouse gas concentrations (primarily CO<sub>2</sub>). Source: Table adopted from report of Working Group I, Table 12.12). Red = high confidence; yellow = medium confidence; green = no anthropogenic signal detectable above natural variability (50% confidence).

Taking wind as an example, the IPCC claims that an anthropogenic signal has **NOT** emerged in average wind speeds, severe windstorms, tropical cyclones, or sand and dust storms, and none are expected to emerge this century even under an extreme emissions scenario. The same applies to drought and fire weather. This table alone suffices to illustrate the gap between IPCC expert assessments of extreme weather and discussions in the popular media and political arenas. As we show below, the Table reflects longstanding conclusions of the IPCC and other assessment bodies. In the next few sections we will simply present without comment excerpts from past assessment reports.<sup>2</sup> In selecting these excerpts, we've focused on the highest-level summaries to avoid accusations of bias through "cherry picking".

## 87.2 Context: detection is not attribution

This chapter is concerned with detection of trends. Chapter 79 looked at causal attribution, with Section 79.4 specifically addressing extreme weather. If no trend is detected then clearly there is no basis for attribution. But even where a trend is observed attribution should not be assumed automatically to follow. Since there is considerable public interest in the question of whether humans are causing trends in extreme weather to get worse it is useful to recall that AR6 Table 12.12 indicates that, for 34 major weather event and impact types, detection of an anthropogenic signal is asserted with *high confidence* in only four of the 34 weather impact categories, and with *medium confidence* in a further four. The IPCC does not claim to have detected an anthropogenic signal in the remaining

<sup>2</sup>In these excerpts we have added **bold face** emphasis while *italicized* emphasis on confidence terms appears in the original sources. Citations in quoted text can be found in the underlying reports but are not reproduced here.

26 categories. Of the four *high confidence* assertions, two are for changes in average temperatures (air and ocean), which are not measures of extreme weather. Also, two of the four *medium confidence* assertions are related to ocean chemistry and are also not related to extreme weather. The IPCC does not assert a detectable human influence on many non-temperature weather features such as wind, precipitation, flooding, and drought.

### 87.2.73 Hurricanes and Tropical Cyclones

The AR6 assessed provides the following assessment of tropical cyclones (TCs; used here to be synonymous with hurricanes):

AR6: There is *low confidence* in most reported long-term (multidecadal to centennial) trends in TC frequency or intensity-based metrics due to changes in the technology used to collect the best-track data. (IPCC, 2021)

AR6: It is *likely* that the global proportion of major (Category 3–5) tropical cyclone occurrence has increased over the last four decades. . . . There is *low confidence* in long-term (multi-decadal to centennial) trends in the frequency of all-category tropical cyclones. (IPCC, 2021)

AR6: A subset of the best-track data corresponding to hurricanes that have directly impacted the United States since 1900 is considered to be reliable, and shows *no trend* in the frequency of U.S. landfall events. (IPCC, 2021)

Since 1980, when satellite observations fully covered the global oceans, we have confidence in the numbers of total global hurricanes and major hurricanes (Category 3 and higher). Figure 87.3.1 shows that on average, each year there are about 50 hurricanes, with about 25 reaching major hurricane status (RN Maue, 2025). Substantial year-to-year and decadal variability is seen; over the time period, there is a slight decreasing trend in the number of hurricanes and a slight but insignificant increasing trend in the number of major hurricanes. From these two trends, it is inferred that there is an overall trend of increasing percentage of major hurricanes, relative to the total number of hurricanes.

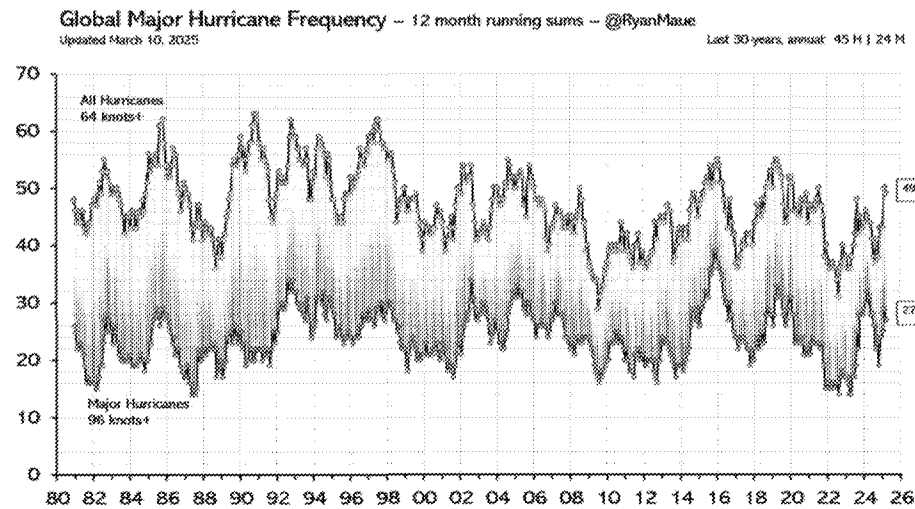


Figure 87.3.1: Global frequency of hurricanes and major hurricanes since 1980.

Global hurricane statistics are dominated by the Northwest Pacific Ocean, which accounts for ~35% of total global hurricanes, whereas the Atlantic accounts for ~15% of global hurricanes (CSU, 2025).

Data in the Atlantic Ocean extends further back than in the other ocean basins, and is most relevant to U.S. policy makers.

Figure 7.3.2 shows the frequency of Atlantic hurricanes (HR) and major hurricanes (MHR, Category 3 and higher) back to 1920. Data prior to 1965 (the onset of satellite observations in the Atlantic, shaded in blue) shows some undercounting, with data prior to 1920 showing substantial undercounting (GA Vecchi and TR Knutson, 2011). All measures of Atlantic hurricane activity show a significant increase since 1970. However, the period from 1971-1994 was a period of exceptionally low activity, with high values of hurricane activity (comparable to the past two decades, even with undercounting) also observed during the 1950's and 1960's, and also in the 1930's.

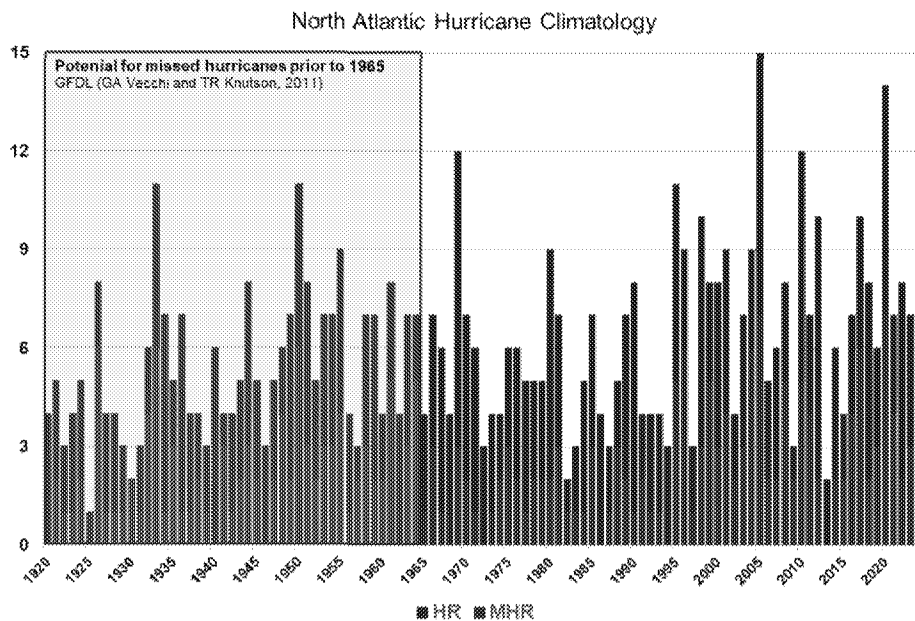


Figure 7.3.2: Atlantic frequency of hurricanes and major hurricanes since 1920. Source (NHC, 2024)

It is seen from Figure 7.3.2 that Atlantic hurricanes show strong variations on decadal and multi-decadal time scales in the observed record. These variations are associated primarily with the Atlantic Multidecadal Oscillation (AMO), which is associated with basin-wide sea surface temperature and sea level pressure fluctuations associated with large scale ocean circulation patterns. The AMO was in its warm phase during 1926-1970 and 1995-present; the AMO was in its cool phase during 1971-1994. The greatest impact of the AMO is on the number of major hurricanes (Category 3+). The relationship of the AMO to major hurricane activity in the Atlantic was identified by Goldenberger et al. (2001) to be associated with above normal SST's and decreased vertical shear associated with the warm AMO (GD Bell and M Chelliah, 2006; PJ Klotzbach et al., 2018).

Klotzbach et al. (2018) conducted a comprehensive evaluation of the landfalling hurricane data for the Continental U.S. since 1900. Figure 8.7.3.3 updates the Klotzbach et al. analysis through 2024. While the largest numbers of hurricanes are from 2004, 2005 and 2020, the overall trend since 1920 is not statistically significant from zero. Figure 8.7.3.3 also shows the time series for major hurricane landfalls (Category 3-5). The largest year in the record is 2005, with 4 major hurricane landfalls. However, during the period 2006 through 2016, there were no major hurricanes striking the U.S., which is the longest such period in the record since 1920.

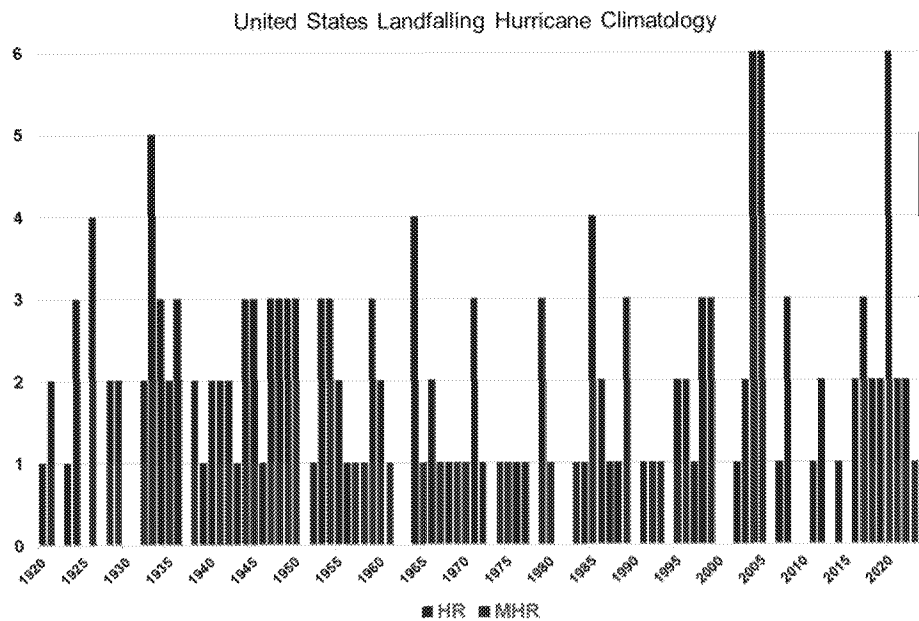


Figure 8.7.3.3: US landfalling frequency of hurricanes and major hurricanes since 1920. Source (NOAA HRD(a), 2024)

Substantial interannual to multidecadal variability in U.S. landfall activity is seen in Klotzbach et al. (2018) examined how the landfall counts vary with ENSO (El Niño versus La Niña) and the warm versus cold phases of the Atlantic Multidecadal Oscillation (AMO).

Villarini et al. (2012) provide an analysis of U.S. hurricane landfalls back to 1878. While it is possible that some landfalls were missed in the late 19<sup>th</sup> century owing to sparsely populated regions on the Gulf Coast, it is remarkable that the highest year in the entire record, with 7 landfalls, is 1886.

Table 8.7.3.1 shows the 10 strongest hurricanes (plus ties) to make U.S. landfall. Of the hurricanes that have made landfall with sustained winds greater than 150 mph, only one has occurred in the busy period since 2004.

Table 8.7.3.1 Strongest hurricanes to make landfall along the US coast. Source (NOAA HRD(b), 2024)



| Rank | Year | Landfall Wind (MPH) | Name          |
|------|------|---------------------|---------------|
| 1    | 1935 | 185                 | "Labor Day"   |
| 2    | 1969 | 175                 | Camille       |
| 3    | 1992 | 165                 | Andrew        |
| 4    | 2018 | 160                 | Michael       |
| 5    | 1856 | 150                 | "Last Island" |
| 5    | 1886 | 150                 | "Indianola"   |
| 5    | 1919 | 150                 | -----         |
| 5    | 1932 | 150                 | "Freeport"    |
| 5    | 2004 | 150                 | Charley       |
| 5    | 2020 | 150                 | Laura         |
| 5    | 2021 | 150                 | Ida           |
| 5    | 2022 | 150                 | Ian           |

While an increase in hurricane intensity has long been hypothesized to occur as global sea surface temperatures increase, identification of any significant trend in the hurricane data is hampered by a short data record and substantial natural variability.

In summary, analyses of both global and regional variability and trends of hurricane activity provide the basis for detecting changes and understanding their causes. The relatively short historical record of hurricane activity, and the even shorter record from the satellite era, is not sufficient to assess whether recent hurricane activity is unusual relative to the background natural variability. Atlantic hurricane processes are influenced substantially by the natural modes of ocean circulation variability in the Atlantic, notably the Atlantic Multidecadal Oscillation. The AR6 assessed this topic as follows:

AR6: There is *low confidence* in most reported long-term (multidecadal to centennial) trends in TC frequency or intensity-based metrics due to changes in the technology used to collect the best-track data. (Chapter 11, p. 1585)

AR6: It is *likely* that the global proportion of major (Category 3–5) tropical cyclone occurrence has increased over the last four decades. There is *low confidence* in long-term (multidecadal to centennial) trends in the frequency of all-category tropical cyclones. (SPM.A.3.4)

AR6: A subset of the best-track data corresponding to hurricanes that have directly impacted the United States since 1900 is considered to be reliable, and shows *no trend in the frequency of U.S. landfall events*. (Chapter 11 Summary, p. 1585)

Hurricane strength records for the North Atlantic and the Western Pacific go back to 1950 and the record does not show an increase in either total or major TCs. Figure 8.3.1 was published by Roger Pielke Jr. as an update to the Best Track data series originally presented in Weinkle et al. (2012).

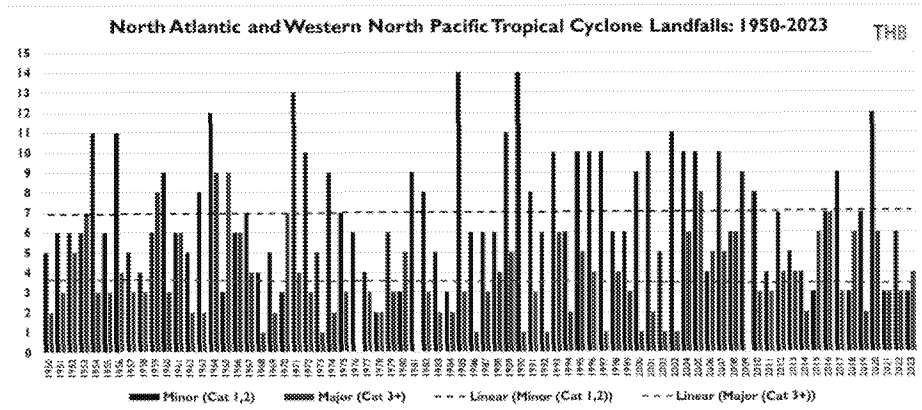


Figure 8.3.1: Tropical Cyclone Landfalls. Source: [HYPERLINK "<https://rogerpielkejr.substack.com/p/global-tropical-cyclones>"] Weimle et al. (2012)

Similarly, Figure 8.3.2 [Maue, 2025] [HYPERLINK "<https://climatlas.com/tropical/>"] shows that both all hurricanes and major hurricanes have not become more common since 1960, the period of rapidly growing human influences. In fact, both numbers have trended down slightly since the 1990s.

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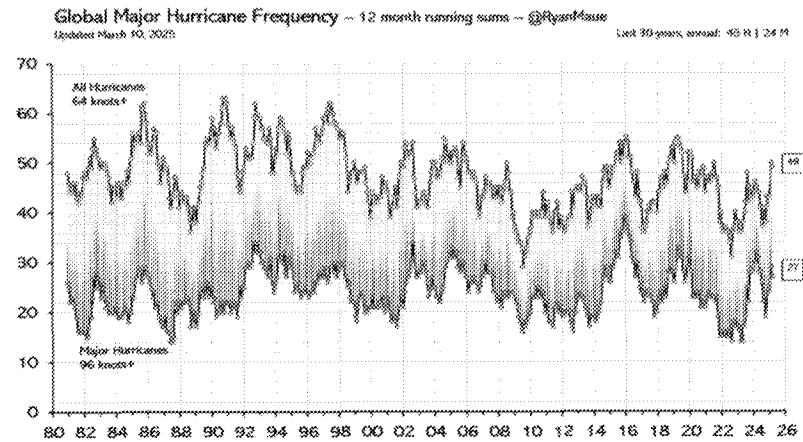


Figure 8.3.2: Global hurricane frequency. Source: Maue (2025)

A metric that combines the number, duration, and strength of TCs is the Accumulated Cyclone Energy (ACE) index maintained at Colorado State University, shown in Figure 8.3.3. It clearly shows no long-term increase in fact declining slightly since 1990.

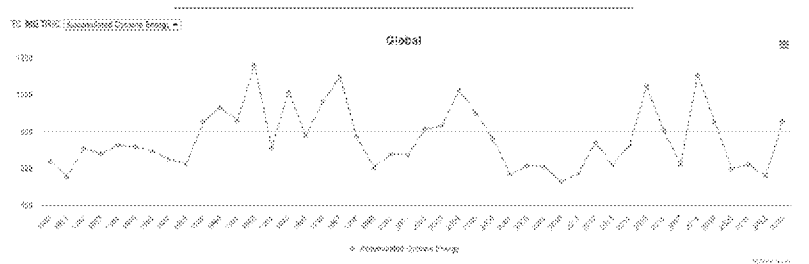


Figure 8.3.3: Global Accumulated Cyclone Energy. Source: Klotzbach (2025)

[HYPERLINK "<https://tropical.atmos.colostate.edu/Realtime/index.php?arch&loc=global>"]

Note that Tu et al. (2024) report that the Power Dissipation Index (PDI), another different measure that combines hurricane number, duration, and strength, has either remained unchanged or has declined in all global oceanic basins since the mid-1990s.

Today's global climate simulations are too coarse to project changes in TCs directly. Rather, projections are derived from finer "downscaled" simulations or proxies involving sea surface temperatures, winds, and aerosols. By those methods, a warming climate is expected to show declining hurricane formation rates (Chang et al. 2022). Climate models also project fewer Tropical Cyclones under future global warming, and even though models project they will increase in strength, the annual averages of rainfall maxima decline (Stancfield et al. 2020).

### 8.3 Tornadoes SREX (p. 159):

There have been no significant trends observed in global tropical cyclone frequency records, including over the present 40-year period of satellite observations (e.g. Webster et al., 2005). Regional trends in tropical cyclone frequency have been identified in the North Atlantic, but the fidelity of these trends is debated (Holland and Webster, 2007; Landsea, 2007; Mann et al., 2007a). Different methods for estimating undercounts in the earlier part of the North Atlantic tropical cyclone record provide mixed conclusions (Chang and Guo, 2007; Mann et al., 2007b; Kunkel et al., 2008; Vecchi and Knutson, 2008). Regional trends have not been detected in other oceans (Chan and Xu, 2009; Kubota and Chan, 2009; Callaghan and Power, 2011). It thus remains uncertain whether any observed increases in tropical cyclone frequency on time scales longer than about 40 years are robust after accounting for past changes in observing capabilities (Knutson et al., 2010).

### AR5 (pp. 216-17):

Current data sets indicate no significant observed trends in global tropical cyclone frequency over the past century and it remains uncertain whether any reported long-term increases in tropical cyclone frequency are robust, after accounting for past changes in observing capabilities (Knutson et al., 2010). No robust trends in annual numbers of tropical storms, hurricanes and major hurricanes counts have been identified over the past 100 years in the North Atlantic basin. Measures of land-falling tropical cyclone frequency

(Figure 2.34) are generally considered to be more reliable than counts of all storms which tend to be strongly influenced by those that are weak and/or short lived. Callaghan and Power (2011) find a statistically significant decrease in Eastern Australia land-falling tropical cyclones since the late 19th century although including 2010/2011 season data this trend becomes non-significant (i.e. a trend of zero lies just inside the 90% confidence interval). Significant trends are not found in other oceans on shorter time scales (Chan and Xu, 2009; Kubota and Chan, 2009; Mohapatra et al., 2011; Weinkle et al., 2012), although Grinsted et al. (2012) find a significant positive trend in eastern USA using tide gauge data from 1923–2008 as a proxy for storm surges associated with land-falling hurricanes. Differences between tropical cyclone studies highlight the challenges that still lie ahead in assessing long-term trends.

In summary, this assessment does not revise the SREX conclusion of *low confidence* that any reported long-term (centennial) increases in tropical cyclone activity are robust, after accounting for past changes in observing capabilities. More recent assessments indicate that **it is unlikely that annual numbers of tropical storms, hurricanes and major hurricanes counts have increased over the past 100 years in the North Atlantic basin.** Evidence, however, is for a virtually certain increase in the frequency and intensity of the strongest tropical cyclones since the 1970s in that region.

AR6 (p. 1585)

**There is low confidence in most reported long-term (multidecadal to centennial) trends in TC frequency or intensity-based metrics due to changes in the technology used to collect the best-track data.** This should not be interpreted as implying that no physical (real) trends exist, but rather as indicating that either the quality or the temporal length of the data is not adequate to provide robust trend detection statements, particularly in the presence of multidecadal variability.

There are previous and ongoing efforts to homogenize the best-track data (Elner et al., 2008; Kossin et al., 2013, 2020; Choy et al., 2015; Landsea, 2015; Emanuel et al., 2018) and there is substantial literature that finds positive trends in intensity-related metrics in the best-track during the “satellite period”, which is generally limited to the past ~40 years (Kang and Elner, 2012; Kishitawala et al., 2012; Kossin et al., 2013, 2020; Mei and Xie, 2016; Zhao et al., 2018; Tavale and Tsuboki, 2019). When best-track trends are tested using homogenized data, the intensity trends generally remain positive, but are smaller in amplitude (Kossin et al., 2013; Holland and Bruyère, 2014). Kossin et al. (2020) extended the homogenized TC intensity record to the period 1979–2017 and identified significant global increases in major TC exceedance probability of about 6% per decade.<sup>2</sup> In addition to trends in TC intensity, there is evidence that TC intensification rates and the

<sup>2</sup>The underlined text referenced a study (Kossin et al. 2020) that later retracted a portion of its findings. Those authors assembled a dataset on global TC intensity spanning 1979 to 2017 from which they claimed that the global fraction of TCs reaching major status (Cat3–5) rose from 27% during 1979–1997 to 31% during 1998–2017 and that the increase was statistically significant. However, closer examination of their results showed a significant increase only in the North Atlantic (15% to 24%) whereas changes in all other basins (Eastern Pacific, Western Pacific, North Indian, South Indian, South Pacific) were not statistically significant in a subsequent correction ([HYPERLINK "https://www.pnas.org/doi/10.1073/pnas.2021573117"]). Kossin et al. stated that the global probability of observing a major TC rose from 24% during 1979–1997 to 27% in the later period and that the evidence for statistical significance was now weaker. Nevertheless, the authors claimed that the correction did not affect their conclusions.

frequency of rapid intensification events have increased within the satellite era (Gschstawal et al. 2012; Balaguru et al. 2018; Bhatia et al. 2018). The increase in intensification rates is found in the best-track as well as the homogenized intensity data.

**A subset of the best-track data corresponding to hurricanes that have directly impacted the United States since 1900 is considered to be reliable, and shows no trend in the frequency of U.S. landfall events (Knutson et al., 2019).**

AR6: "[O]bservational trends in tornadoes, hail, and lightning associated with severe convective storms are not robustly detected due to insufficient coverage of the long-term observations. There is medium confidence that the mean annual number of tornadoes in the USA has remained relatively constant." (Chapter 11, section 11.7.3, p. 1504)

As noted there is no evidence of trend in US tornadoes or extreme convective storms. Extreme precipitation will be discussed further below.

#### 8.7.34 Temperature extremes

The AR6 assessment focused on the period after 1950 and reported increasing trends in heat wave frequency and intensity. The NCA17 however noted that heat wave activity in the US reached a peak in the 1930s.

AR6: "It is *virtually certain* that hot extremes (including heatwaves) have become more frequent and more intense across most land regions since the 1950s, while cold extremes (including cold waves) have become less frequent and less severe" (SPM, A3.1)

AR6: "In North America, there is very robust evidence for a *very likely* increase in the intensity and frequency of hot extremes and decrease in the intensity and frequency of cold extremes for the whole continent, though there are substantial spatial and seasonal variations in the trends. Minimum temperatures display warming consistently across the continent, while there are more contrasting trends in the annual maximum daily temperatures in parts of the USA." (Chapter 11, p. 1550)

NCA17: "Changes in warm extremes are more nuanced than changes in cold extremes. For instance, the warmest daily temperature of the year increased in some parts of the West over the past century, but there were decreases in almost all locations east of the Rocky Mountains. In fact, all eastern regions experienced a net decrease, most notably the Midwest (about 2.2°F [1.2°C]) and the Southeast (roughly 1.5°F [0.8°C])." (pp. 190-191)

NCA17: "Since the mid-1960s, there has been only a very slight increase in the warmest daily temperature of the year (amidst large interannual variability). Heat waves (6-day periods with a maximum temperature above the 90th percentile for 1961–1990) increased in frequency until the mid-1930s, became considerably less common through the mid-1960s, and increased in frequency again thereafter. As with warm daily temperatures, heat wave magnitude reached a maximum in the 1930s." (pp. 190-191)

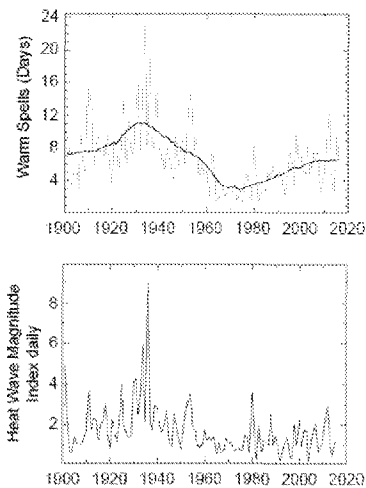


Figure 8-7.34.1: US Heat waves since 1900. Source: NCA17 Figure 6.4

#### 8-7.34.1 Temperatures in the US are becoming less extreme

Daily maximum temperatures in the warm season (TMax, May-Sep) and daily minimum temperatures in the cold season (TMin, Dec-Mar) are available beginning in Dec 1898 (126 years). The dataset consists of 1,211 CONUS stations designated as United States Historical Climate Network or USHCN stations (see Figure 8-7.34.32; Quinlan et al. 1987, Karl et al. 1990). These stations were selected by NOAA as having the fewest problematic issues with gaps, station moves and instrument changes. Where gaps still exist, nearby stations (bias-corrected) were merged so that the median volume of data available for a station is 98%. Although there are certainly errors in the dataset, with over 1,000 stations we can have relatively high confidence in any underlying signal that might be discovered.

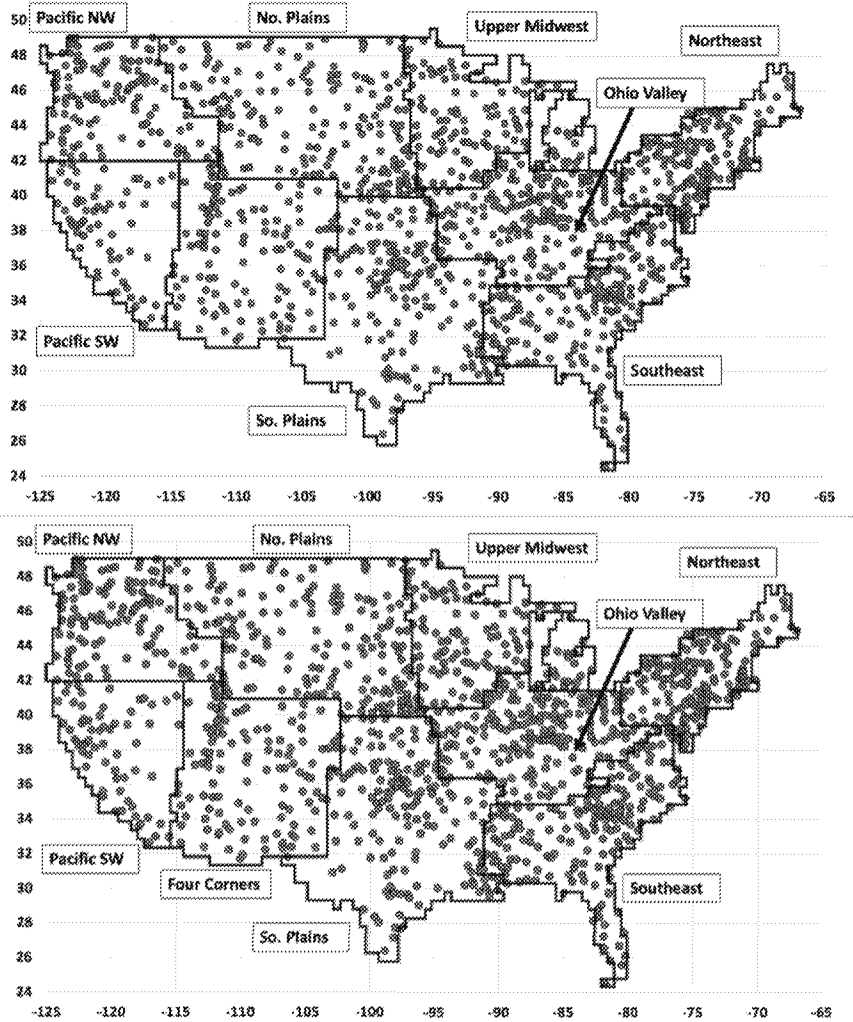


Figure 8-7.34.42 Locations of USHCN temperature stations. Source: USHCN.

We begin with the question of whether the occurrence of daily record high or low temperatures changed has changed since Dec 1898. Each warm-season has 153 days (1 May to 30 Sep) and each cold-season has 122 days (1 Dec to 31 Mar). For each station and day, we calculated the year in which the record highest (lowest) temperature occurred. With 126 years of observations, if there were no temperature trends over time, the expected number of records for TMax would be 1.21 ( $=153/126$ ) per station per year and for TMin 0.96 ( $=122/126$ ) per station per year. Figure 8-7.4-34.3 indicates the observed distribution in time of the occurrence of these extreme events.

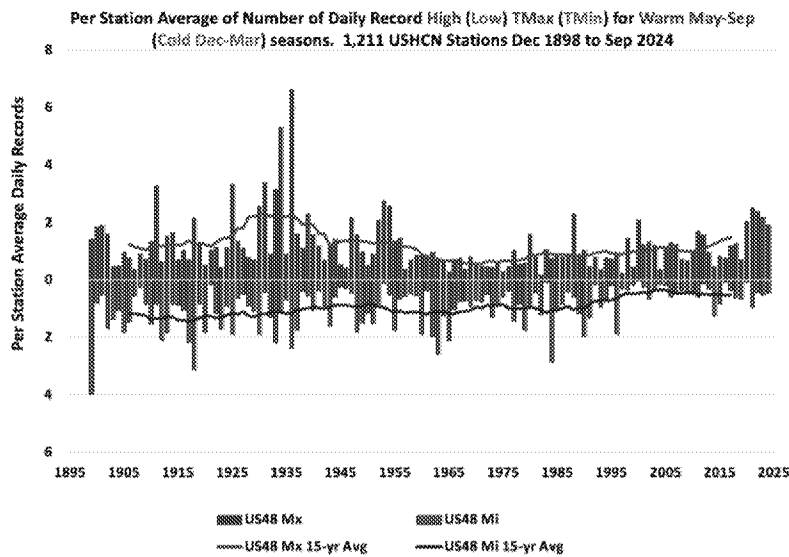


Figure 8-7.34.23 Number of daily record High (red) and Low (blue) for warm and cold seasons in the CONUS. The lines represent the 15-year running, centered average. Source: 1,211 USHCN stations supplemented as needed to achieve a minimum of 92% of observations in the 126-year period since Dec. 1898.

The results indicate a common feature in many metrics of warm-season extremes in the CONUS - the exceptional heat of the 1920s and especially the 1930s, peaking in 1936. On a per-station average, 60% of the TMax records and 59% of the TMin records occurred in the first half of the period (1899-1961).

On the cold side, the Valentine's Day Arctic outbreak in Feb. 1899 stands as the most extensive cold extreme experienced by the CONUS, with 1917 2<sup>nd</sup>. The frequency of cold records has declined, especially over the last quarter of the period in which only 13% of the extreme cold events were measured. In contrast, 25% of the extreme TMax records were achieved in the last quarter in accordance with statistical expectations. These general features have been noted in past assessments (see above, IPCC AR5, IPCC AR6, NCA4, NCA5 [7]). Combining the two records the overall reduction in numbers of both cold and hot extremes over the past century indicates a climate less prone to extremes.

This pattern is also shown in Figure 8-7.34.24. For each station and for each year the hottest warm season and coldest cold-season temperatures were calculated and converted to anomalies relative to the station's long-term warm and cold season (respectively) averages. Then the differences between these were computed by station and geographically-averaged over all stations, thus yielding an

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annual measure of the expected range of local extreme temperatures for each year. Figure 8.7.4.4.1 shows the 15-year trailing average of this measure which has clearly declined over the past century.

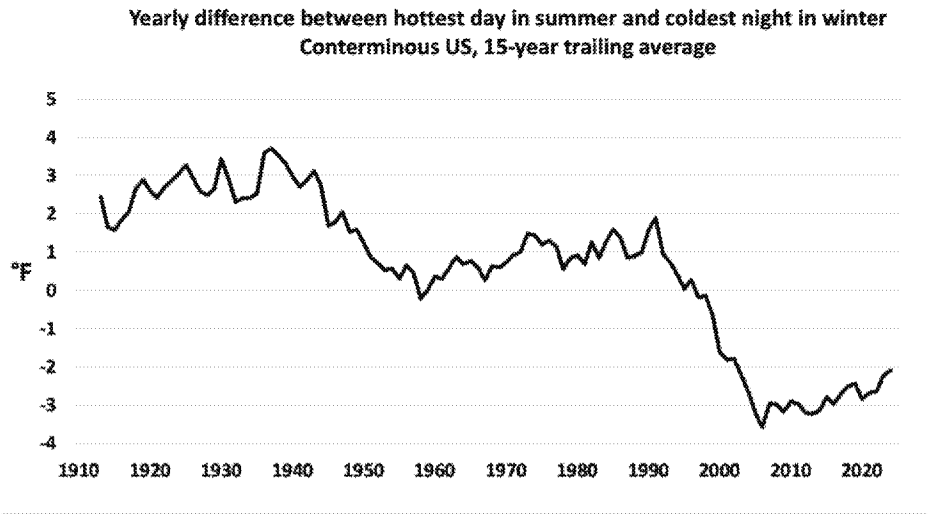


Figure 8.7.4.4.1. 15-year trailing average of the difference each year of each station's hottest warm-season TMax and coldest cold-season TMin relative to the long-term average. Source: USHCN, author calculations.

The average difference for each station between the hottest summer TMax and coldest winter TMin has declined about 5°F in the past 126 years. The decline is due mostly to warming winter TMin, but a decline in the magnitude of summer TMax is also a factor. The rise in TMin has been strongly related to the growing presence of manufactured surfaces around the weather stations over the last 100+ years (Spencer et al. 2025).

Summarizing Figures 8.7.4.4.2.3 and 8.7.4.4.3.4.4, while temperature extremes are regularly experienced in the US and attract a great deal of media attention, long term records show the US climate has become less extreme over time (milder) when measured in terms of the range between warm season maxima and cold season minima.

#### 8.7.4.4.2 Exceedances of a heat threshold

Under the heading of "The Risk of Temperature Extremes is Changing", the most recent US National Climate Assessment report (NCA235) notes the increase in a threshold metric of number of days at or above 95°F, stating,

"The western US has been particularly affected by extreme heat since the 1980s .... experiencing a larger increase in days over 95°F, as would be expected given the greater warming in that region relative to the eastern US. Several major heatwaves have affected the US since 2018, including a record-shattering event in the Pacific Northwest in 2021."

Are the occurrences of 95°F days changing? In a climate as varied as that of CONUS, threshold statistics can be misleading. A region with many stations that have near 95°F TMax average temperatures in the summer might see large swings in the metric when only small changes in average temperature occur. Elsewhere with stations that either rarely or virtually always achieve 95°F TMax temperatures, a small change will not impact the results much at all. In the past 126 years, the average CONUS station experienced 129 days exceeding 95°F per 6-yr period, but the regional values range from 278 in the Southern Plains to 9 in the Northeast. Thus, one needs to view such threshold analyses with caution.

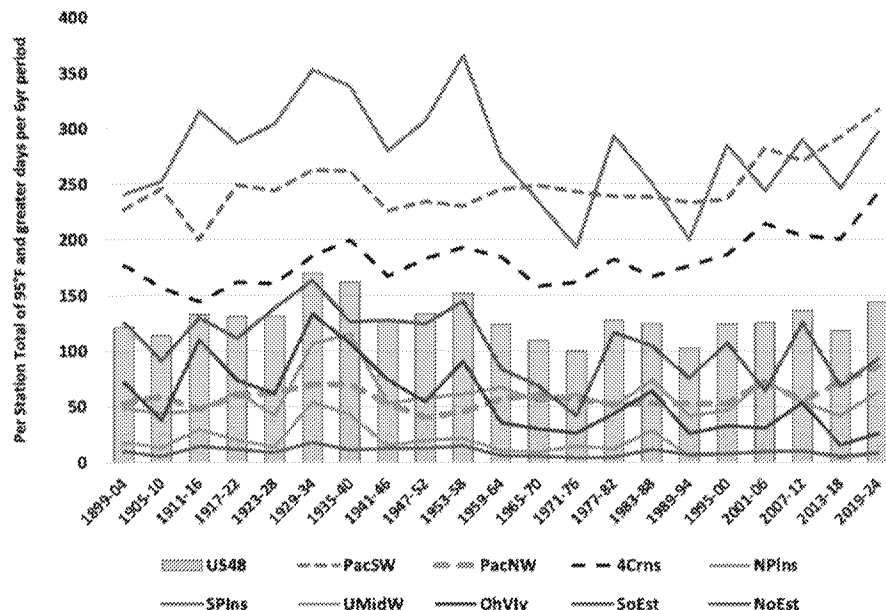


Figure 8-7.4-334.45. Total number of days  $\geq 95^{\circ}\text{F}$  in 6-yr periods. US 48 (bars) and regions (lines). Interval is 6-years as this is divisible into 126. Source: USHCN, author calculations.

In Fig. 8-7.4-334.45 we see that only three of the nine regions, all in the West, have experienced upward trends in the number of 95°F or hotter days (dashed lines). The CONUS as a whole has not and the other six regions have experienced declines.

The Pacific NW heatwave of 2021 is referenced as of the NCA523 claim, an event we examine more closely in Section 6.4. The evidence indicates it was a “black swan” event, i.e., a single, unprecedented event in the record, not part of a pattern of increasing extreme heat. For example, the 5-day average tropospheric grid-point temperature anomaly over the Pacific NW during that event was +10.8 C, the most extreme NH grid point summer anomaly in the 46 years from over 4 million grid values. In contrast, the global anomaly during that time was virtually zero (+0.03 C, Mass et al. 2024).

The heading “The Risk of Temperature Extremes is Changing” suggests positive trends are now being observed in threshold temperatures on a widespread basis, but that is not evidenced in the combined CONUS results of the figures above.

#### 8.7.4.324.3 Heatwaves

Heatwaves (consecutive days that exceed an extreme threshold) have a greater societal impact than a single daily record. We measure “Heatwave Days” here as the count of all days in May-Sep each year that exceed the 90<sup>th</sup> percentile and that lie within a run of at least six consecutive days. This is equivalent to the method used in NCA517 except that the reference period here is the entire record 1899-2024, while NCA517 truncated the reference period to 1961-1990, a cool time. That truncation boosts positive results (days exceeding the 90<sup>th</sup> percentile) in periods warmer than the reference period, especially starting in 1960 and moving to the present (see *Urban Influences* below).

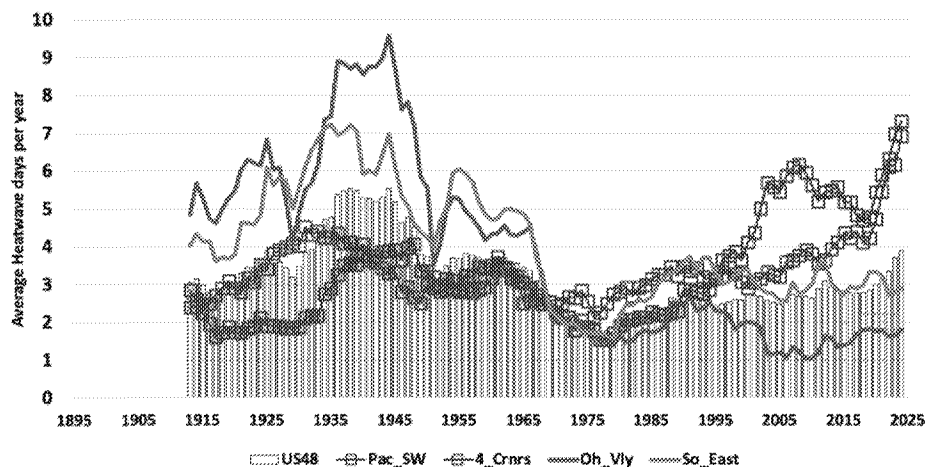


Figure 8.7.4.34.56 15-year trailing average of number of heatwave days per year per station in the CONUS (bars) and four regions: Pac SW (purple squares, CA, NV), 4 Crnrs (red squares, AZ, NM, UT, CO), Oh\_Vly (blue, MO, IL, KY, TN, IN, OH, WV) and So\_East (green, MS, AL, GA, FL, SC, NC, VA).

Figure 8.7.4.34.56 indicates again the excessive heat of the first half of the 20<sup>th</sup> century, primarily in the eastern two-thirds of the nation, as seen in the regional values for the Ohio Valley and the

Southeast as examples. The West has seen a recent increase of heatwave days and the two regions with the highest number are shown, the Pacific Southwest and the Four-Corners (NCAE23). This indicates that the background warm season circulation favored heatwaves in the eastern portions of the country in the first half of the 20<sup>th</sup> century, but in the 21<sup>st</sup> century the patterns have favored heatwaves in the West. For CONUS as a whole, heatwaves are no more common today than they were a century ago.

Of interest here is the regional variation of this metric. The four northern regions (Pacific NW, Northern Plains, Upper Midwest and Northeast) on average experience 15 to 27 heatwave days per 15-year period. In contrast, the five southern regions (Pacific Southwest, 4-Corners, Southern Plains, Ohio Valley and Southeast) see 37 to 54 such days, essentially twice as many. This suggests the summer circulation pattern is more prone to stationary events in the southern regions while transient systems in the northern regions are more common and thus cut short these potentially longer events.

#### 8.7.34.4 Urban influences

The NCAE23 directs readers to the website [HYPERLINK "<https://www.globalchange.gov/indicators/heat-waves>"] (USGCRP 2023) to view the number of urban heatwaves by decade from the 1960s. The figure shows a monotonic increase in each decade from 2 occurrences per year in the 1960s to 6 in the 2020s. The definition of a heatwave is an unusual but practical measure of human discomfort - a period of at least 2 consecutive days when the minimum apparent temperature (combination of temperature and humidity) exceeds the 85<sup>th</sup> percentile. Note too, the dataset is limited to the 50 largest U.S. cities.

These increasing values since 1960 presented in USGCRP (2023) are entirely reasonable, but are unrelated to GHG emissions for at least two reasons. Urbanization in these cities is a major factor in the rise of TMin relative to co-located TMax and relative to TMin at rural stations. Also, the 1960s was the coldest decade and 1970s the second coldest decade since the 1910's, so this starting date preconditions the time series to show increases. This does not dismiss the real rise in nighttime temperatures in major U.S. cities and the societal impacts associated with these changes. However, we note for a variety of reasons, that summer TMax (especially in rural areas) serves as better response variable for detecting potential changes in heatwaves influenced by changes in the background climate due, for example, to increasing GHGs (Christy et al. 2009). For the CONUS as a whole, the evidence in this section suggests GHG emissions have had little-to-no effect on heatwaves.

#### 8.4 Tornadoes

AR6: [O]bservational trends in tornadoes, hail, and lightning associated with severe convective storms are not robustly detected due to insufficient coverage of the long-term observations. There is medium confidence that the mean annual number of tornadoes in the USA has remained relatively constant. (Chapter 11, section 11.7.3, p.1594)

As noted there is no evidence of trends in US tornadoes or extreme convective storms. Extreme precipitation will be discussed below.

#### 8.7.455 Extreme precipitation

The IPCC AR6 assessed that an increase in heavy precipitation has been observed in data starting in the 1950s.

AR6: "The frequency and intensity of heavy precipitation events have increased since the 1950s over most land area for which observational data are sufficient for trend analysis (high confidence)." (SPM A3.2)

AR6: "In North America, there is robust evidence that the magnitude and intensity of extreme precipitation has *very likely* increased since the 1950s. Both [one-day maximal and 5-day maximal] have significantly increased in North America during 1950-2018" (Chapter 11, p. 1560)

However other data sources indicate less evidence of increasing extreme precipitation when examined over a longer time scale.

Figure 8.7.3.845.1 shows that US long term data from NOAA (1895-2023) shows an insignificantly increasing tendency toward extreme wetness (+0.0001% per year)

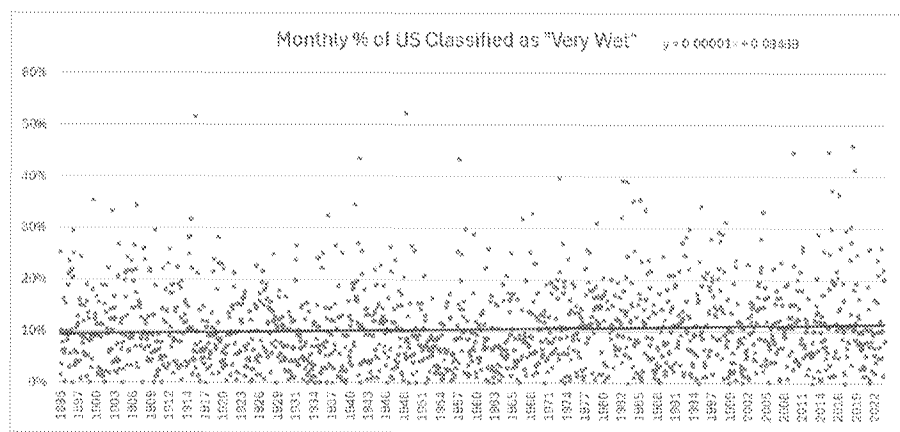
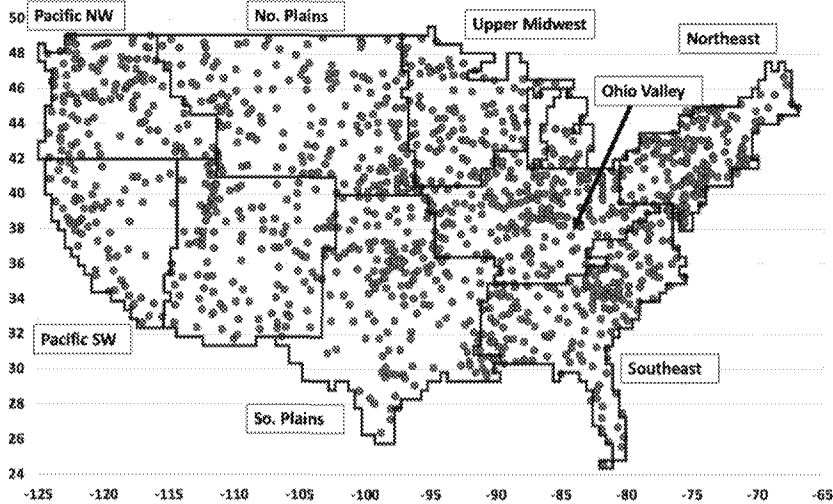


Figure 8.7.45.1: Long term US wetness (%). Source: NOAA [HYPERLINK "<https://www.ncei.noaa.gov/access/monitoring/uspa/wet-dry/0/>"]

Because precipitation involves a discrete phase change (water vapor to liquid), it is stochastic and episodic in character and requires careful statistical treatment to understand variability over long time periods (see 8.7.1 Introduction). The US National Climate Assessments (NCA417, NCA523) have highlighted an increase in the occurrence of the heaviest precipitation events (defined in different ways) primarily in the eastern half of the CONUS, especially the Northeast, when starting in either 1901 or 1958. Interestingly, the regional variations indicate that the largest increases in extreme events are in the Northeast and the smallest in the West, a trend counter to the changes in temperature extremes.

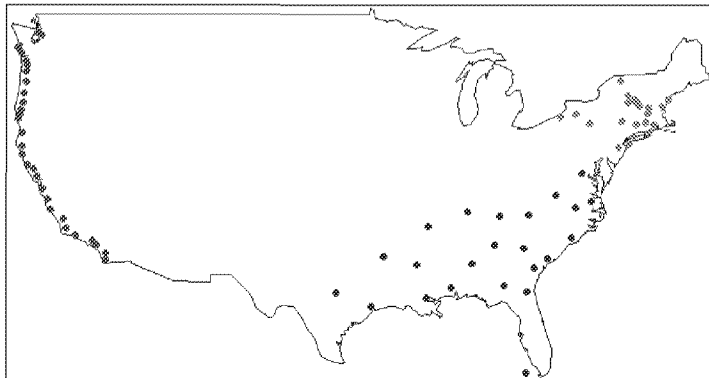
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McKittrick and Christy (2019) examined long-term and consistent station observations of extreme daily precipitation to test some of these NCA claims for the Southeast and West Coast. When the time series were extended back in time (as far as 1872 in some cases) or when starting later (1978), there were no significant trends for either region.

For this report we updated these findings with similarly constructed observations from 29 stations on the CONUS Pacific Coast (1893ff from San Diego CA to Blaine WA) and 24 stations in the humid Southeast (1872ff from Austin TX to Washington DC), and also adding 21 stations in the Northeast (1868ff from Buffalo NY to Gardiner ME). The locations are shown in Figure 7.5.2. The results of applying the analysis of McKittrick and Christy (2019) were as follows for each region, then, indicating the statistical updates followed by further explanations.



map of stations-RM]

{will generate

Figure 7.5.2: Locations of precipitation monitoring stations used in this report. Green: Pacific coast. Blue: Northeast. Red: Southeast.

#### Pacific region:

- .....Average precipitation trend is significant (downwards) in Astoria, insignificant elsewhere.
- .....The trend in rainfall variance is positive and significant in Big Sur, insignificant elsewhere.
- .....The trend in daily maximum precipitation is positive and significant in Aberdeen and Big Sur and negative and significant in Newport (insignificant elsewhere).
- .....Averaged over all stations in the region none of these three trend parameters is statistically significant.

#### Southeast region:

- .....The trend in average precipitation is positive and significant in Mobile and Quitman, insignificant elsewhere.
- .....The trend in rainfall variance is positive and significant in Mobile, insignificant elsewhere.
- .....The trend in daily maximum precipitation is positive and significant in Vicksburg and Norfolk, insignificant elsewhere.
- .....Averaged over all stations in the region none of these three trend parameters is statistically significant.

#### Northeast region:

- .....The trend in average precipitation is positive and significant in 9 of 21 locations and in the region averaged overall.
- .....The trend in rainfall variance is positive and significant in Portland, Albany and Buffalo, insignificant elsewhere.
- .....The trend in daily maximum precipitation is positive and significant in Portland and Gardiner, insignificant elsewhere.
- .....Averaged over all stations in the region the trend parameters for variance and maximum precipitation are not statistically significant.

#### Pacific Coast heavy rainfall events

- \* Average precipitation trend is significant (downwards) in Astoria, OR, insignificant elsewhere.
- \* The trend in rainfall variance is positive and significant in Big Sur, CA, insignificant elsewhere.
- \* The trend in daily maximum precipitation is positive and significant in Aberdeen, WA and Big Sur, CA and negative and significant in Newport, OR (insignificant elsewhere).
- \* Averaged over all stations in the region none of these three trend parameters is statistically significant.

The Pacific Coast receives considerable precipitation from Atmospheric River (AR) events which often last more than a day or two (e.g., Gershunov et al. 2017, Pan et al. 2024). The worst-known such series of events in recent history was the so-called ARekStorm that occurred between December 1861 and January 1862, which dumped nearly 10 feet of rain in parts of California and submerged the entire Central Valley for weeks under as much as 15 feet of water (Erewer 1930, Null and Hulbert 2007). Additionally, Paleoclimate research has found six megastorms more severe than 1861–1862 in California during the last 1800 years, occurring at intervals of 300 years or so (Porter et al. 2011).

#### SIDEBAR: Perils of short data records

San Francisco provides a good case study of the limitation of using short historical samples to characterize natural variability of extreme events. Suppose we use a 130-year sample of daily San Francisco precipitation from 1895 to 2024 and we look for 3-day, 5-day, 14-day and 30-day rainfall records. The results are as shown in Table 8-7.2.

| Event  | Record (inches) | Year |
|--------|-----------------|------|
| 3-day  | 6.94            | 2023 |
| 5-day  | 8.55            | 2023 |
| 14-day | 12.62           | 2023 |
| 30-day | 18.93           | 1998 |

Table 8-7.2: Extreme rainfall records, San Francisco, 1895-2024.

The records all cluster in the more recent data. 2023 appears to be an exceptional year and since it is near the end of the sample it might suggest that the climate has shifted into a more hazardous state, perhaps as a result of human influences. [Note: "2023" indicates the event occurred in the water-year of Aug 2022 to Jul 2023.]

But the picture is very different if we use a sample that begins 45 years earlier, in 1850. Table 8-7.3 shows that the record-setting events then all happened in the 1860s. Furthermore 2023 is now not even in 2<sup>nd</sup> place but falls to 3<sup>rd</sup> or 4<sup>th</sup>. Also, comparing the records of the two charts, the extreme precipitation events in 1862 and 1867 involved considerably more rainfall than the 1998 and 2023 events, with 14- and 30-day totals about 50 percent higher.

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| Event  | Record (inches) | Year | Rank of 130-yr extreme |
|--------|-----------------|------|------------------------|
| 3-day  | 8.85            | 1867 | 3                      |
| 5-day  | 9.80            | 1867 | 3                      |
| 14-day | 19.05           | 1862 | 4                      |
| 30-day | 28.25           | 1862 | 2                      |

Table 8-7.3: Extreme rainfall records, San Francisco, 1850-2024.

The range of natural variability is made even more remarkable when paleoclimate evidence is examined. Porter et al. (2011) discovered that in the past 1,800 years at least six megastorms were more intense than the devastating 1861-62 ARkStorm that struck the region. Evidently such extreme events, "unprecedented" in our 1895-2024 sample, have impacted the region about every 300 years, though not since 1895.

This example illustrates the limitations of using relatively short climate periods (~130 years) to assess the character and range of natural variability in general and of extreme events in particular. Accurate representation of the full range of natural variability is necessary for any attribution analyses (see 6.4). Infrastructure planners, emergency management institutions and attribution scientists would understand the significant mischaracterization of the magnitude of a future extreme if based only on the last 130 years. In this case a single time-sample of 130 years provides an underestimation of the extreme value by up to 50% determined when adding only 45 more years of observations. Compared to millennial-scale paleoclimate evidence, an even greater underestimation would occur. An important lesson is that the climate can deliver great surprises on its own, even without human influences.



We examine occurrences of 5-day deluges as follows. In a 130-year span there are 26 5-year intervals. At each location we computed the 5-day precipitation totals throughout the year and selected the 26 highest values. A single year may have more than one of the 26 heaviest. Each of those can be thought of as 1-in-5yr events. If there are no trends in precipitation then the total number of these events across all stations should be evenly spread out over the years. In Fig. 8.7.4.5.1 we show the distribution in time of these events. The deluges associated with the massive 1997-98 El Niño event are readily apparent. While erratic, as is typical of these types of precipitation metrics, there is no indication of a tendency to become more frequent over time.

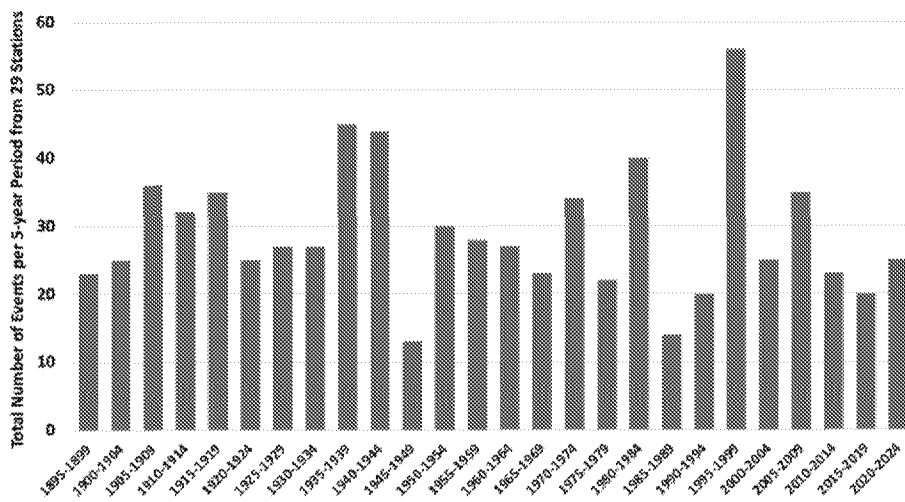


Figure 8.7.5.24-5. The time distribution by 5-year periods of the 26 heaviest occurrences for each station (i.e., nominal 1-in-5-year event) for stations along the Pacific Coast of the CONUS.

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#### Southeast heavy rainfall events

- \* The trend in average precipitation is positive and significant in Mobile AL and Quitman GA, insignificant elsewhere.
- \* The trend in rainfall variance is positive and significant in Mobile AL, insignificant elsewhere.
- \* The trend in daily maximum precipitation is positive and significant in Vicksburg MS and Norfolk VA, insignificant elsewhere.
- \* Averaged over all stations in the region none of these three trend parameters is statistically significant.

The temporal pattern of 5-day totals of the 1-in-5yr heavy events in the humid Southeast (Figure 8.7.4.6.5.2) is generally unremarkable, though a cluster of higher values appears in 1995 to 2019. The increase in those years is due largely to the 4 northeastern-most stations of Wilmington NC, Weldon NC, Washington DC, and Norfolk VA. This confirms the pattern indicated in NCA417 and NCA523 of

a tendency for an increasing frequency of heavy events, due to a temporal clustering of tropical storms from eastern NC to Maine discussed below. Otherwise the remaining 20 stations show an unremarkable temporal distribution of heavy events.

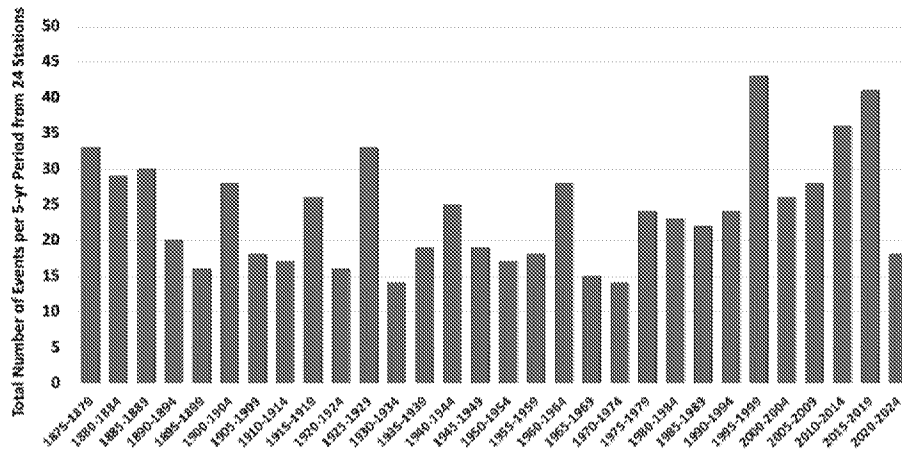


Figure 9-7.4-65.3. As above but for the 30 heaviest 1-in-5-yr events for 24 stations in the humid Southeast from Austin TX to Washington DC in 5-year bins for 1975-2024.

#### Northwest heavy rainfall events

- \* The trend in average precipitation is positive and significant in 9 of 21 locations and in the region averaged overall.
- \* The trend in rainfall variance is positive and significant in Portland ME, Albany NY and Buffalo NY, insignificant elsewhere.
- \* The trend in daily maximum precipitation is positive and significant in Portland ME and Gardner ME, insignificant elsewhere.
- \* Averaged over all stations in the region the trend parameters for variance and maximum precipitation are not statistically significant.

Fig. 9-7.4-25.3 shows the 27 (1-in-5-yr) heaviest 3-day events for the last 135 years in 21 stations in the Northeast (including Montreal Canada). We use 3-day totals here as this produced the largest variations in time. In this region, 72% of the events occur during June to October and are dominated by tropical incursions of hurricanes, tropical storms or tropical storms that transition to extratropical systems. According to NCA417 and NCA523 this region experienced the largest increases in extreme events, so it shall be examined more closely.

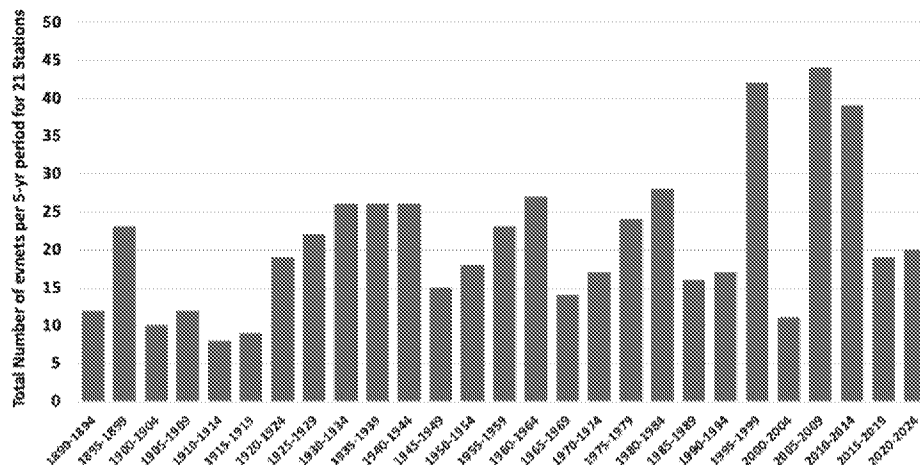


Figure 8-7.4-75.4. Time distribution of the heaviest 27 (1-in-5-yr) heaviest 3-day precipitation events for 21 stations from NY to ME, including Montreal.

Howarth et al. (2019) report differences in the Northeast-between two 18-year periods: 1979-96 and 1997-2014 (a similar region as in Fig. 8-7.4-65.4 that includes PA and NJ) of various precipitation extremes. One metric which indicated a dramatic increase (317%) was found for 24-hr events > 6 inches. This high increase is due to the very small numbers of such events of which there were only 6 in the first period and 25 in the second as reported for 58 stations. This high percentage increase is due to the very small numbers of the events; only 6 in the first period and 25 in the second. Most of the stations did not record such an event suggesting these erratic, episodic events over brief 18-yr periods need scrutiny by additional statistical methods.

Using the information in Fig. 8-7.4-75.4 over the same years as Howarth et al. we find a 51% increase in the frequency of heavy events between the two periods. One can see in Fig. 8-7.4-65.4 that it was unfortunate that Howarth et al. ended in 2014 prior to a return to the long-term average of such events.

A feature of Howarth et al. is the use of single day totals which is questionable because extreme events are often spread across the time-of-observation boundary. Thus stations measuring at 0700 LT versus those at Midnight will have differing results for a particular event which would then have major impacts on counting these events. We use the 3-day totals in Fig. 8-7.4-75.4 to be sure to capture the extent of these extreme downpours. In any case, we can confirm that the period 1997 to 2014 experienced a cluster of heavier events as Howarth et al. have documented.

Howarth's most remarkable claim (317% increase in 6" days) is potentially misleading because it is a threshold statistic (see Section 8-4.2-8-7.3.2 above) and a ratio of small numbers over a short period. The result is not representative of relative extreme events for the whole region since the majority of stations never experienced a 6" total. Figure 8-7.4-65.4 above determines the same number of events for each station (27 heaviest events) whose heaviest values ranged from 4.4" to 12.5" and their 27<sup>th</sup> heaviest values ranged from 3.3" to 5.0". This analysis thus allows each station to

be equally represented. In other words, if there is a region-wide increase in heavy events, it should be seen in the sum of all stations. Note too that the period of record here is 135 years vs. 36 years of Howarth et al. Except for three 5-year periods between 1995 and 2014 there is nothing statistically remarkable about the results in Fig. 8.7.4.7.

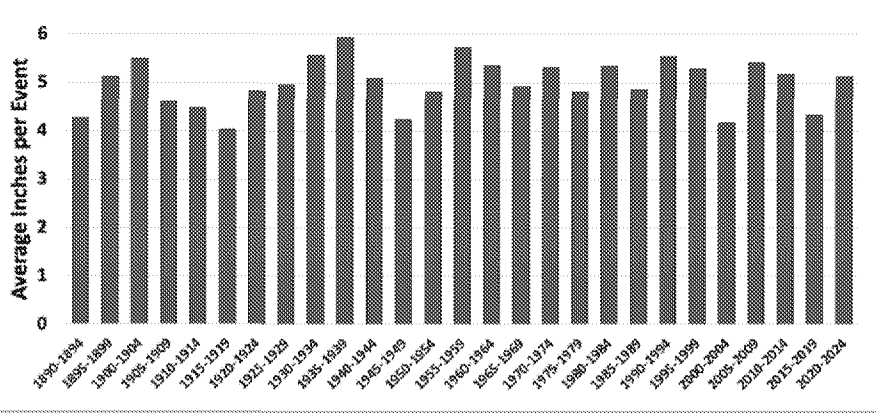


Figure 8.7.4.85.5. Average amount of precipitation falling in the 1-in-5yr events for the NE stations.

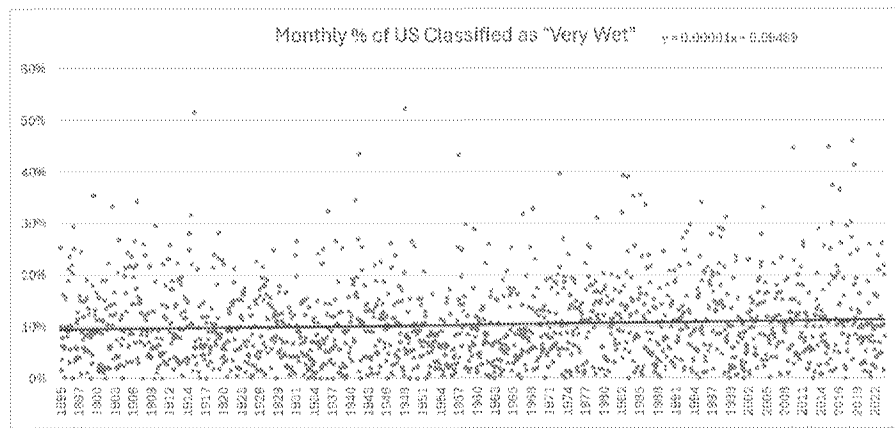
An interesting aspect of Northeast precipitation is that there has been no change in the amount of precipitation per heaviest event, as shown in Fig. 8.7.4.85.5. The trend is only +0.02"/decade. The highest amount, 1935-39, includes the Great New England Hurricane of 1938, one of the rare major (Category 3 or higher) hurricanes to strike the region. The results in Figs. 8.7.4.45.4 and 8.7.4.25.5 suggest that though there was an uptick in the number of events during the period 1995 to 2014, the events, individually, are not becoming more intense.

long et al. (2024) document the increase of tropical influences on precipitation events in the Northeast since 1959 and concluded, "The autumn extreme precipitation trend over the Northeast US is primarily attributed to tropical cyclone-related events since the 1990s." The question then becomes, was the temporal clustering of tropical systems in 1997-2014 which affected the Northeast a response to increasing GHGs (see Chapter 9 Attribution)? long et al. examined CMIP-6 model output which suggests that there will be fewer such systems in the 21st century but that the intensity of the rainfall events might increase. This conjecture is not seen in Fig. 8.7.4.75.5 where the amount-per-event has remained steady over the 135-year period.

For substantial urban areas there is some evidence to indicate the heaviest rainfall events may be redistributed due to the impact urban infrastructure has on the local weather (e.g., Pielke Sr. et al. 2011, Zhang et al. 2018, Yang et al. 2024). Yang et al. state, "Cities that experience compact development tend to witness larger increases in extreme rainfall frequency over downtown than their rural surroundings, while the anomalies in extreme rainfall frequency diminish for cities with

dispersed development.” While this is an important insight to consider, the effect on the specific stations used in this analysis is unknown, or at least not detectable in Fig. 8.7.4.2.5.

In summary, the evidence from the historical record of extreme precipitation events in the CONUS is generally not consistent from region to region so that inferences regarding trends and their projections are wrought with significant uncertainty. In most regions and perhaps all, it is our analysis here opinion suggests that given the very nature of the erratic and episodic character of extreme precipitation events, changes that can be confidently categorized as significant relative to natural variability have not been observed renders the discovery of statistically significant changes, including a relationship to CO<sub>2</sub> concentrations, a result yet to be achieved (McKittrick and Christy 2019).



#### 8.7.6 Tornadoes

AR6: [O]bservational trends in tornadoes, hail, and lightning associated with severe convective storms are **not robustly detected** due to insufficient coverage of the long-term observations. There is *medium confidence* that the mean annual number of tornadoes in the USA has remained relatively constant. (Chapter 11, section 11.7.3, p. 1594)

As noted there is no evidence of trends in US tornadoes or extreme convective storms.

Figure 8.2.84.1: Long-term US wetness (%). Source: NOAA [HYPERLINK "<https://www.ncei.noaa.gov/access/monitoring/uspa/wet-dry/0>"]

### 8.7.2.27 Flooding

Changes in floods were assessed as follows:

AR6: "The SREX assessed *low confidence* for observed changes in the magnitude or frequency of floods at the global scale. This assessment was confirmed by the AR5 report. The SR1.5 found increases in flood frequency and extreme streamflow in some regions, but decreases in other regions. ... [H]ydrological literature on observed flood changes is heterogeneous, focusing at regional and sub-regional basin scales, making it difficult to synthesise at the global and sometimes regional scales." (Chapter 11.5)

AR6: "[T]he seasonality of floods has changed in cold regions where snowmelt dominates the flow regime in response to warming (*high confidence*). Confidence about peak flow trends over past decades on the global scale is *low*." (Chapter 11.5)

NCA17: "Trends in extreme high values of streamflow are mixed across the United States. Analysis of 200 U.S. stream gauges indicates areas of both increasing and decreasing flooding magnitude but does not provide robust evidence that these trends are attributable to human influence." (pp. 240-241)

The absence of detectable US-wide trends in flooding is consistent with the findings in the previous section of absence of coherent changes in extreme precipitation.

SREX (p. 176)

In the United States and Canada during the 20th century and in the early 21st century, there is no compelling evidence for climate-driven changes in the magnitude or frequency of floods.

AR5 (p. 214)

AR4 WGI Chapter 3 (Trenberth et al., 2007) did not assess changes in floods but AR4 WGI concluded that there was not a general global trend in the incidence of floods (Kundzewicz et al., 2007). SREX went further to suggest that there was low agreement and thus *low confidence* at the global scale regarding changes in the magnitude or frequency of floods or even the sign of changes.

AR5 WGI assesses floods in regional detail accounting for the fact that trends in floods are strongly influenced by changes in river management (see also Section 7.5.2). Although the most evident flood trends appear to be in northern high latitudes, where observed warming trends have been largest, in some regions no evidence of a trend in extreme flooding has been found, for example, over Russia based on daily river discharge (Shiklomanov et al., 2007). Other studies for Europe (Hannaord and Marsh, 2008; Renard et al., 2009; Petrov and Merz, 2009; Stahl et al., 2010) and Asia (Qiang et al., 2008; Delgado et al., 2010) show evidence for

upward, downward or no trend in the magnitude and frequency of floods, so that there is currently no clear and widespread evidence for observed changes in flooding except for the earlier spring flow in snow-dominated regions (Seneviratne et al., 2012). In summary, there continues to be a lack of evidence and thus low confidence regarding the sign of trend in the magnitude and/or frequency of floods on a global scale.

AR6 (Ch. 11 p. 1562)

The SREX (Seneviratne et al., 2012) assessed low confidence for observed changes in the magnitude or frequency of floods at the global scale. This assessment was confirmed by the AR5 report (Hartmann et al., 2013). The SR15 (Hoegh-Guldberg et al., 2018) found increases in flood frequency and extreme streamflow in some regions, but decreases in other regions. While the number of studies on flood trends has increased since the AR5 report, and there were also new analyses after the release of SR15 (Berghuis et al., 2017; Blöchl et al., 2019; Gudmundsson et al., 2019), hydrological literature on observed flood changes is heterogeneous, focusing at regional and sub-regional basin scales, making it difficult to synthesise at the global and sometimes regional scales.

In summary, the seasonality of floods has changed in cold regions where snowmelt dominates the flow regime in response to warming (high confidence). Confidence about peak flow trends over past decades on the global scale is low, but there are regions experiencing increases, including parts of Asia, southern South America, the northeast USA, northwestern Europe, and the Amazon, and regions experiencing decreases, including parts of the Mediterranean, Australia, Africa, and the southwestern USA.

US NCA12, pp. 740-41:

"The IPCC AR5 did not attribute changes in flooding to anthropogenic influence nor report detectable changes in flooding magnitude, duration, or frequency. Trends in extreme high values of streamflow are mixed across the United States. Analysis of 200 U.S. stream gauges indicates areas of both increasing and decreasing flooding magnitude, but does not provide robust evidence that these trends are attributable to human influences."

The complex mix of processes complicates the formal attribution of observed flooding trends to anthropogenic climate change and suggests that additional scientific rigor is needed in flood attribution studies. As noted above, precipitation increases have been found to strongly influence changes in flood statistics. However, in U.S. regions, no formal attribution of precipitation changes to anthropogenic forcing has been made so far, so indirect attribution of flooding changes is not possible. Hence, no formal attribution of observed flooding changes to anthropogenic forcing has been claimed."

## 8.2.3 Heatwaves

AR5 (p. 212 WG1)

Table 2.13 shows that there has been a likely increasing trend in the frequency of heatwaves since the middle of the 20th century in Europe and Australia and across much of Asia where there are sufficient data. However, confidence on a global scale is medium owing to lack of studies over Africa and South America but also in part owing to differences in trends depending on how heatwaves are defined (Perkins et al., 2012). Using monthly means as a proxy for heatwaves, Coumou et al. (2013) and Hansen et al. (2012) indicate that record-breaking temperatures in recent decades substantially exceed what would be expected by

chance but caution is required when making inferences between these studies and those that deal with multi-day events and/or use more complex definitions for heatwave events. There is also evidence in some regions that periods prior to the 1950s had more heatwaves (e.g., over the USA, the decade of the 1930s stands out and is also associated with extreme drought conditions (Peterson et al., 2013)) whereas conversely in other regions heatwave trends may have been underestimated owing to poor quality and/or consistency of data (e.g., Della-Marta et al. (2007a) over Western Europe; Kuglitsch et al. (2009, 2010) over the Mediterranean). Recent available studies also suggest that the number of cold spells has reduced significantly since the 1950s (Donat et al. 2013a, 2013c).

In summary, new analyses continue to support the AR4 and SREX conclusions that since about 1950 it is *very likely* that the numbers of cold days and nights have decreased and the numbers of warm days and nights have increased overall on the global scale that in far land areas with sufficient data it is *likely* that such changes have also occurred across most of North America, Europe, Asia and Australia.

#### NGA17 (pp. 190-191)

Changes in warm extremes are more nuanced than changes in cold extremes. For instance, the warmest daily temperature of the year increased in some parts of the West over the past century (Figure 6.3), but there were decreases in almost all locations east of the Rocky Mountains. In fact, all eastern regions experienced a net decrease (Table 6.2), most notably the Midwest (about  $-2.2^{\circ}\text{F}$  [ $-1.2^{\circ}\text{C}$ ]) and the Southeast (roughly  $-1.5^{\circ}\text{F}$  [ $-0.8^{\circ}\text{C}$ ]). The decreases in the eastern half of [the] Nation, particularly in the Great Plains, are mainly tied to the unprecedented summer heat of the 1930s Dust Bowl era, which was exacerbated by land surface feedbacks driven by springtime precipitation deficits and land mismanagement. However, anthropogenic aerosol forcing may also have reduced summer temperatures in the Northeast and Southeast from the early 1950s to the mid-1970s, and agricultural intensification may have suppressed the hottest extremes in the Midwest.

Since the mid-1960s, there has been only a very slight increase in the warmest daily temperature of the year (amidst large interannual variability). Heat waves (6-day periods with a maximum temperature above the 90th percentile for 1961–1990) increased in frequency until the mid-1930s, became considerably less common through the mid-1960s, and increased in frequency again thereafter (Figure 6.4). As with warm daily temperatures, heat wave magnitude reached a maximum in the 1930s.



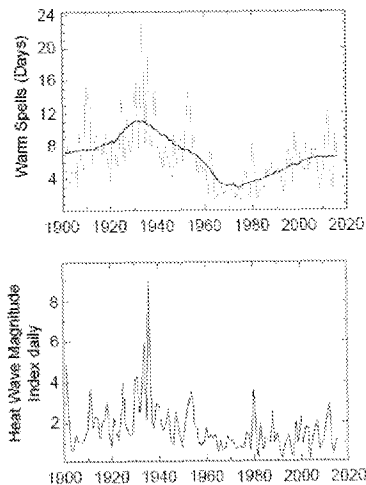


Figure 8.2.1: US Heat waves since 1900. Source: NCA17 Figure 6.4

AR6 (p. 1550)

In North America (Table 11.19), there is very robust evidence for a *very likely* increase in the intensity and frequency of hot extremes and decrease in the intensity and frequency of cold extremes for the whole continent, though there are substantial spatial and seasonal variations in the trends. Minimum temperatures display warming consistently across the continent, while there are more contrasting trends in the annual maximum daily temperatures in parts of the USA (Figure 11.9; Lee et al., 2014; van Oldenborgh et al., 2019; Dunn et al., 2020).

#### 8.2.4 Extreme snowfall events

Note: extreme snowfall events in the US northeast are assessed in relation to winter Extratropical Cyclone (ETC) activity.

AR6 Ch.11, p. 1593

There is *high confidence* that snowfall associated with winter ETCs will decrease in the future, because increases in tropospheric temperatures lead to a lower proportion of precipitation falling as snow (O’Gorman, 2014; Rhoades et al., 2019; Zarzycki, 2018). However, there is *medium confidence* that extreme snowfall events associated with winter ETCs will change little in regions where snowfall will be supported in the future (O’Gorman, 2014; Zarzycki, 2018).

#### 8.2.5 Extreme precipitation

#### SREX (p. 147)

Recent studies have updated the assessment of the AR4, with more regional results now available (Table 3-2). Overall, this additional evidence confirms that more locations and studies show an increase than a decrease in extreme precipitation, but that there are also wide regional and seasonal variations, and trends in many regions are not statistically significant (Table 3-2). Based on station data from Canada, the United States, and Mexico, Peterson et al. (2008a) reported that heavy precipitation has been increasing over 1950–2004, as well as the average amount of precipitation falling on days with precipitation.

#### ARE (pp. 212–14)

In summary, further analyses continue to support the AR4 and SREX conclusions that it is likely that since 1951 there have been statistically significant increases in the number of heavy precipitation events (e.g., above the 95th percentile) in more regions than there have been statistically significant decreases, but there are strong regional and subregional variations in the trends. In particular, many regions present statistically non-significant or negative trends, and, where seasonal changes have been assessed, there are also variations between seasons (e.g., more consistent trends in winter than in summer in Europe). The overall most consistent trends towards heavier precipitation events are found in central North America (very likely increases) but assessment for Europe shows likely increases in more regions than decreases.

#### AR6 (p. 1560)

In North America, there is robust evidence that the magnitude and intensity of extreme precipitation has very likely increased since the 1950s. Both one-day maximal and 15-day maximal have significantly increased in North America during 1950–2018 (Sun et al., 2020, also Figure 11.12). There is, however, regional diversity. In Canada, there is a lack of detectable trends in observed annual maximum daily (or shorter duration) precipitation (Shephard et al., 2014; Makis et al., 2015; Vincent et al., 2016).

#### NCA17 pp. 213–14

Detectability of trends (compared to internal variability) for a number of precipitation metrics over the continental United States has been examined; however, trends identified for the U.S. regions have not been clearly attributed to anthropogenic forcing. One study concluded that increasing precipitation trends in some north-central U.S. regions and the extreme annual anomalies there in 2013 were at least partly attributable to the combination of anthropogenic and natural forcing. Based on current evidence, it is concluded that detectable but not attributable increases in mean precipitation have occurred over parts of the central United States. Formal detection-attribution studies indicate a human contribution to extreme precipitation increases over the continental United States, but confidence is low based on those studies alone due to the short observational period, high natural variability, and model uncertainty.

In summary, based on available studies, it is concluded that for the continental United States there is high confidence in the detection of extreme precipitation increases, while there is low confidence in attributing the extreme precipitation changes purely to anthropogenic forcing.

### 2.2.6 Tornadoes and severe convective storms

Severe convective storms are convective systems that are associated with extreme phenomena such as tornadoes, hail, heavy precipitation (rain or snow), strong winds, and lightning.

The assessment of changes in severe convective storms in SREX (Chapter 3, Senaviratne et al., 2012) and AR5 (Chapter 12, Collins et al., 2013) is limited and focused mainly on tornadoes and hail storms. The SREX assessed that there is *low confidence in observed trends in tornadoes and hail* because of data inhomogeneities and inadequacies in monitoring systems. Subsequent literature assessed in the Climate Science Special Report (Kossin et al., 2017) led to the assessment of the observed tornado activity over the 2000s in the USA, with a decrease in the number of days per year with tornadoes and an increase in the number of tornadoes on these days (*medium confidence*). However, there is *low confidence in past trends for hail and severe thunderstorm winds*. Climate models consistently project environmental changes that would support an increase in the frequency and intensity of severe thunderstorms that combine tornadoes, hail, and winds (*high confidence*), but there is *low confidence* in the details of the projected increase.

In summary, because the definition of severe convective storms varies depending on the literature and the region, it is not straightforward to make a synthesizing view of observed trends in severe convective storms in different regions. In particular, *observational trends in tornadoes, hail, and lightning associated with severe convective storms are not robustly detected due to insufficient coverage of the long-term observations*. There is *medium confidence* that the mean annual number of tornadoes in the USA has remained relatively constant, but their variability of occurrence has increased since the 1970s, particularly over the 2000s, with a decrease in the number of days per year, and an increase in the number of tornadoes on these days (*high confidence*). Detected tornadoes have also increased in Europe, but the trend depends on the density of observations.

In summary, it is extremely difficult to detect and attribute changes in severe convective storms. There is limited evidence that extreme precipitation associated with severe convective storms has increased in some cases.

## 8.2.7 Hurricanes and Tropical Cyclones

SREX (p. 159):

There have been no significant trends observed in global tropical cyclone frequency records, including over the present 40-year period of satellite observations (e.g., Webster et al., 2005). Regional trends in tropical cyclone frequency have been identified in the North Atlantic, but the fidelity of these trends is debated (Holland and Webster, 2002; Landsea, 2007; Mann et al., 2007a). Different methods for estimating undercounts in the earlier part of the North Atlantic tropical cyclone record provide mixed conclusions (Chang and Geo, 2007; Mann et al., 2007b; Kunkel et al., 2008; Vecchi and Knutson, 2009). Regional trends have not been detected in other oceans (Chan and Yu, 2009; Kubota and Chan, 2009; Callaghan and Power, 2011). It thus remains uncertain whether any observed increases in tropical cyclone frequency on time scales longer than about 40 years are robust after accounting for past changes in observing capabilities (Knutson et al., 2010).

AR5 (pp. 216–17):

Current data sets indicate no significant observed trends in global tropical cyclone frequency over the past century and it remains uncertain whether any reported long-term increases in tropical cyclone frequency are robust after accounting for past changes in observing capabilities (Knutson et al., 2010). No robust trends in annual numbers of tropical storms, hurricanes and major hurricanes counts have been identified over the past 100 years in the North Atlantic basin. Measures of land-falling tropical cyclone frequency (Figure 2.24) are generally considered to be more reliable than counts of all storms which tend to be strongly influenced by those that are weak and/or short-lived. Callaghan and Power (2011) find a statistically significant decrease in Eastern Australia land-falling tropical cyclones since the late 19th century although including 2010/2011 season data this trend becomes non-significant (i.e., a trend of zero lies just inside the 90% confidence interval). Significant trends are not found in other oceans on shorter time scales (Chan and Xu, 2009; Kubota and Chan, 2009; Mohapatra et al., 2011; Weinkle et al., 2012), although Grinstead et al. (2012) find a significant positive trend in eastern USA using tide gauge data from 1923–2009 as a proxy for storm surges associated with land-falling hurricanes. Differences between tropical cyclone studies highlight the challenges that still lie ahead in assessing long-term trends.

In summary, this assessment does not revise the SREX conclusion of low confidence that any reported long-term (centennial) increases in tropical cyclone activity are robust after accounting for past changes in observing capabilities. More recent assessments indicate that it is unlikely that annual numbers of tropical storms, hurricanes and major hurricanes counts have increased over the past 100 years in the North Atlantic basin. Evidence, however, is for a virtually certain increase in the frequency and intensity of the strongest tropical cyclones since the 1970s in that region.

AR6 (p. 1525)

There is low confidence in most reported long-term (multidecadal to centennial) trends in TC frequency or intensity-based metrics due to changes in the technology used to collect the best-track data. This should not be interpreted as implying that no physical (real) trends exist, but rather as indicating that either the quality or the temporal length of the data is not adequate to provide robust trend detection statements, particularly in the presence of multidecadal variability.

There are previous and ongoing efforts to homogenize the best-track data (Elsner et al., 2008; Kossin et al., 2013, 2020; Choy et al., 2015; Landsea, 2015; Emanuel et al., 2018) and there is substantial literature that finds positive trends in intensity-related metrics in the best-track during the “satellite period”, which is generally limited to the past ~40 years (Kang and Elsner, 2012; Kishitani et al., 2012; Kossin et al., 2013, 2020; Mei and Xie, 2016; Zhao et al., 2018; Tawale and Tumboli, 2019). When best-track trends are tested using homogenized data, the intensity trends generally remain positive but are smaller in amplitude (Kossin et al., 2013; Holland and Bruyere, 2014). Kossin et al. (2020) extended the homogenized TC intensity record to the period 1979–2017 and identified significant global increases in major TC exceedance probability of about 6% per decade. In

<sup>4</sup>The underlined text referenced a study (Kossin et al. 2020) that later retracted a portion of its findings. Those authors assembled a dataset on global TC incidence spanning 1979 to 2017 from which they claimed that the global fraction of TCs reaching major status (Cat 3–5) rose from 2.7% during 1979–1992 to 3.1% during 1996–2017 and that the increase was statistically significant. However, closer examination of their results showed a significant increase only in the North Atlantic (1.6% to 3.4%) whereas changes in all other basins (Eastern

~~addition to trends in TC intensity, there is evidence that TC intensification rates and the frequency of rapid intensification events have increased within the satellite era (Kishore et al. 2012; Balaguru et al. 2018; Bhatia et al. 2018). The increase in intensification rates is found in the best tracks as well as the homogenized intensity data.~~

~~A subset of the best track data corresponding to hurricanes that have directly impacted the United States since 1900 is considered to be reliable, and shows no trend in the frequency of U.S. landfall events (Knutson et al. 2019).~~

### 8.7.2.868 Droughts

Assessments of drought trends were as follows.

AR6: "Few AR6 regions show observed increases in meteorological drought" (Section 11.9, p. 1575).

AR6: "Increasing trends in agricultural and ecological droughts have been observed on all continents (*medium confidence*), but decreases only in one AR6 region (*medium confidence*). Increasing trends in hydrological droughts have been observed in a few AR6 regions." (Chapter 11 Summary)

NCA17: "As a consequence of this increased precipitation, drought statistics over the entire CONUS have declined." (p. 233)

NCA17: "Recent droughts and associated heat waves have reached record intensity in some regions of the United States; however, by geographical scale and duration, the Dust Bowl era of the 1930s remains the benchmark drought and extreme heat event in the historical record (*very high confidence*)." (p. 231)

SREX: "From a paleoclimate perspective, recent droughts are not unprecedented, with severe 'megadroughts' reported in the paleoclimatic record for Europe, North America, and Australia." (p. 170)

US NCA17 REPORT (Ch. 8, Wehner et al. 2017)

p. 231:

~~Recent droughts and associated heat waves have reached record intensity in some regions of the United States; however, by geographical scale and duration, the Dust Bowl era of the 1930s remains the benchmark drought and extreme heat event in the historical record (*very high confidence*). While by some measures drought has decreased over much of the continental United States in association with long-term increases in precipitation, neither the precipitation increases nor inferred drought decreases have been confidently attributed to anthropogenic forcing.~~

~~Pacific, Western Pacific, North Indian, South Indian, South Pacific) were not statistically significant in a subsequent correction ([HYPERLINK "<https://www.pnas.org/doi/10.1073/pnas.2021573117>"]). Kossin et al. stated that the global probability of observing a major TC rose from 24% during 1979-1997 to 37% in the later period and that the evidence for statistical significance was now weaker. Nevertheless, the authors claimed that the correction did not affect their conclusions.~~

The human effect on recent major U.S. droughts is complicated. Little evidence is found for a human influence on observed precipitation deficits, but much evidence is found for a human influence on surface soil moisture deficits due to increased evapotranspiration caused by higher temperatures. (High confidence.)

p. 223:

Drought is, of course, directly connected to seasonal precipitation totals. Figure 7-1 shows detectable observed recent changes in seasonal precipitation. In fact, the increases in observed summer and fall precipitation are at odds with the projections in Figure 7-5. As a consequence of this increased precipitation, drought statistics over the entire CONUS have declined.

SREX (p. 170)

From a paleoclimate perspective recent droughts are not unprecedented, with severe 'megadroughts' reported in the paleoclimatic record for Europe, North America, and Australia (Jansen et al., 2007). Recent studies extend this observation to African and Indian droughts (Sinha et al., 2007; Shanahan et al., 2009); much more severe and longer droughts occurred in the past centuries with widespread ecological, political, and socioeconomic consequences. Overall, these studies confirm that in the last millennium several extreme droughts have occurred (Breda and Haddou, 2008; Kellie, 2008; Bunting et al., 2010).

In North America, there is medium confidence that there has been an overall slight tendency toward less dryness (wetting trend with more soil moisture and runoff; Table 3-2), although analyses for some subregions also indicate tendencies toward increasing dryness. This assessment is based on several lines of evidence, including simulations with different hydrological models as well as RGS and CDS estimates (Alexander et al., 2006; Andreadis and Lettenmaier, 2006; van der Schrier et al., 2006a; Kunkel et al., 2008; Sheffield and Wood, 2008a; Dai, 2011).

The most severe droughts in the 20th century have occurred in the 1930s and 1950s, where the 1930s Dust Bowl was most intense and the 1950s drought most persistent (Adreadis et al., 2005) in the United States, while in Mexico the 1950s and late 1990s were the driest periods. Recent regional trends toward more severe drought conditions were identified over southern and western Canada, Alaska, and Mexico, with subregional exceptions (Dai, 2011).

SREX (p. 172)

Overall, though new studies have furthered the understanding of the mechanisms leading to drought, there is still relatively limited evidence to provide an attribution of observed changes, in particular given the issues associated with the availability of observational data (Section 3.2.1) and the definition and computation of drought indicators (Box 2-3). This latter point was mostly identified in post-AR4 studies (Box 2-3). Moreover, regions where consistent increases in drought are identified (see 'Observed Changes') are only partly consistent with those where projections indicate an enhancement of drought conditions in coming decades (see next paragraphs). We thus assess that there is medium confidence (see also Section 3.1.5) that anthropogenic influence has contributed to some changes in the drought patterns observed in the second half of the 20th century, based on its attributed impact on precipitation and temperature changes (though temperature can only

be indirectly related to drought trends; see Box 3-3). However there is *low confidence* in the attribution of changes in droughts at the level of individual regions.

AR5 (pp. 214–215)

Based on evidence since AR4, SREX concluded that there were not enough direct observations of dryness to suggest high confidence in observed trends globally, although there was *medium confidence* that since the 1950s some regions of the world have experienced more intense and longer droughts. The differences between AR4 and SREX are due primarily to analyses post-AR4, differences in how both assessments considered drought and updated IPCC uncertainty guidance.

Because drought is a complex variable and can at best be incompletely represented by commonly used drought indices, discrepancies in the interpretation of changes can result. For example, Sheffield and Wood (2008) found decreasing trends in the duration, intensity and severity of drought globally. Conversely, Dai (2011a,b) found a general global increase in drought, although with substantial regional variation and individual events dominating trend signatures in some regions (e.g., the 1970s prolonged Sahel drought and the 1930s drought in the USA and Canadian Prairies). Studies subsequent to these continue to provide somewhat different conclusions on trends in global drought and/or dryness since the middle of the 20th century (Sheffield et al., 2012; Dai, 2013; Donat et al., 2013c; vander Schrier et al., 2013).

In summary, the current assessment concludes that there is not enough evidence at present to suggest more than *low confidence* in a global-scale observed trend in drought or dryness (lack of rainfall) since the middle of the 20th century, owing to lack of direct observations, geographical inconsistencies in the trends, and dependencies of inferred trends on the index choice. Based on updated studies, AR4 conclusions regarding global increasing trends in drought since the 1970s were probably overestimated. However, it is *likely* that the frequency and intensity of drought has increased in the Mediterranean and West Africa and decreased in central North America and north-west Australia since 1950.

AR6 (Drought, Observed trends, Section 11.6.2, pp. 1573–75)

p. 1573

Strong precipitation deficits have been recorded in recent decades in the Amazon (2005–2010), south-western China (2009–2010), south-western North America (2011–2014), Australia (1997–2009), California (2014), the middle East (2012–2016), Chile (2010–2015), the Great Horn of Africa (2011), among others (van Dijk et al., 2013; Mann and Gleick, 2015; Rowell et al., 2015; Morango and Espinoza, 2016; Dai and Zhao, 2017; Garreaud et al., 2017, 2020; Morango et al., 2017; Brito et al., 2018; Cook et al., 2018). Global studies generally show no significant trends in SPI time series (Orlowsky and Seneviratna, 2013; Spinoni et al., 2014) and in derived drought frequency and severity data (Spinoni et al., 2019), with very few regional exceptions (Section 11.9 and Figure 11.17).

p. 1574

For AR6 regions, several studies suggest an increase in the frequency and areal extent of soil moisture deficits, with examples in East Asia (Cheng et al., 2015; Y. Qin et al., 2015; Jia et al., 2018), Western and Central Europe (Trnka et al., 2015b), and the Mediterranean (Jlani et al., 2018; Moravec et al., 2019; Markonis et al., 2021). Nonetheless, some analyses also show no long-term trends in soil drying in some AR6 regions – for example, in Eastern

North America (Park Williams et al., 2017) and Central North America (Seager et al., 2019), as well as in North Eastern Africa (Kew et al., 2021).

There is evidence based on streamflow records of increased hydrological droughts in East Asia (D. Zhang et al., 2016) and southern Africa (Gudmundsson et al., 2019). In areas of Western and Central Europe and Northern Europe, there is no evidence of changes in the severity of hydrological droughts since 1950 based on flow reconstructions (Caillaud et al., 2017; Barker et al., 2019) and observations (Vicente-Serrano et al., 2019). In North America, depending on the methods, datasets and study periods, there are differences between studies that suggest an increase (Shukla et al., 2015; Udall and Overpeck, 2017) versus a decrease in hydrological drought frequency (Mo and Lettenmaier, 2018), but in general there is strong spatial variability (Pechirri and Pol, 2016). Streamflow observation reference networks of near-natural catchments have also been used to isolate the effect of climate trends on hydrological drought trends in a few regions, but these show limited trends in Northern Europe and Western and Central Europe (Stahl et al., 2010; Bard et al., 2015; Harrigan et al., 2018), North America (Dudley et al., 2020) and most of Australia, with the exception of Eastern and Southern Australia (X.S. Zhang et al., 2016).

#### p.1575

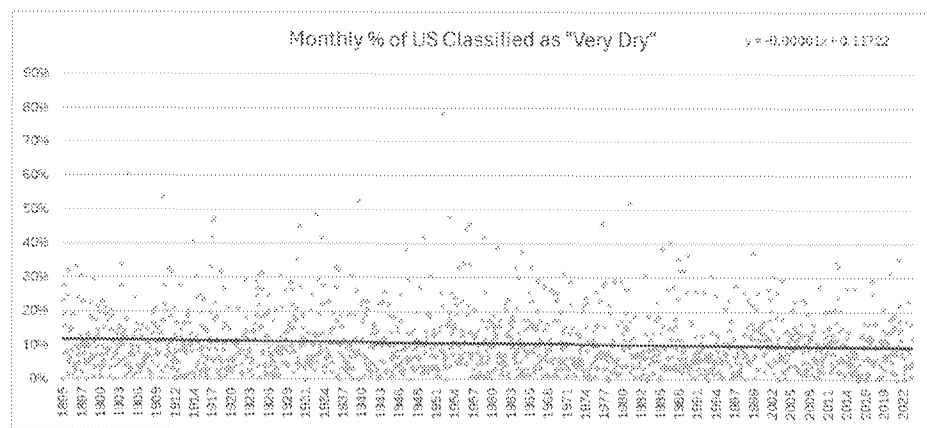
Few AR6 regions show observed increases in meteorological drought (Section 11.2), mostly in Africa and South America (NES: *high confidence*; WAF, CAF, WSAF, SAM, SWS, SSA, SAS: *medium confidence*); a few others show a decrease (WSB, ESB, NAU, CAL, NEU, CNA: *medium confidence*). There are stronger signals indicating observed increases in agricultural and ecological drought (Section 11.3), which highlights the role of increased (evapo)transpiration, driven by increased (Atmospheric Evaporative Demand), for these trends (Sections 11.6.2.3, 11.6.2.5). Past increases in agricultural and ecological droughts are found on all continents and several regions (WAF, CAF, WSAF, SSAF, WCA, ECA, EAS, CAL, MED, WCE, NES: *medium confidence*), while decreases are found only in one AR6 region (NAU: *medium confidence*). The more limited availability of datasets makes it more difficult to assess historical trends in hydrological drought at regional scale (Section 11.9). Increasing (MED: *high confidence*; WAF, EAS, SAU: *medium confidence*) and decreasing (NEU, SES: *medium confidence*) trends in hydrological droughts have only been observed in a few regions.

#### AR6 on Attribution (p. 1577)

There are only two AR6 regions in which there is at least *medium confidence* that human-induced climate change has contributed to changes in meteorological droughts (Section 11.9). In South-western South America (SSW), there is *medium confidence* that human-induced climate change has contributed to an increase in meteorological droughts (Weisler et al., 2016; Garreaud et al., 2020), while in Northern Europe (NEU), there is *medium confidence* that it has contributed to a decrease in meteorological droughts (Gudmundsson and Seneviratne, 2016) (Section 11.9). In other AR6 regions, there is inconclusive evidence in the attribution of long-term trends, but a human contribution to single meteorological events or subregional trends has been identified in some instances. In North America, the human influence on precipitation deficits is complex (Wehner et al., 2017), with low confidence in the attribution of long-term changes in meteorological drought in AR6 regions.



As shown in Figure 8.7.3-968.1 US long term data (NOAA) shows an insignificantly declining tendency toward extreme dryness (-0.001% per year)



**Figure 8.7.3-968.1:** US dryness (%) 1895—2023. Source: NOAA [HYPERLINK <https://www.ncei.noaa.gov/access/monitoring/uspa/wet-dry/0>]

Kogan et al. (2020) examines a 38-year high-resolution satellite-based drought measure and concludes that global drought has not intensified and is not connected to climate change: "it is possible to state firmly that global and main grain countries' drought area and intensity trends have not been following global climate warmings since 1980's."

### 8.32 Extreme weather trends at Global and continental indicators of scale extreme weather trends

#### 8.32.1 Tropical Cyclones (TCs)

Hurricane-strength records for the North Atlantic and the Western Pacific go back to 1950 and the record does not show an increase in either total or major TCs. Figure 8.3.1 was published by Roger Pielke Jr. as an update to the Best Track data series originally presented in Weinko et al. (2012).

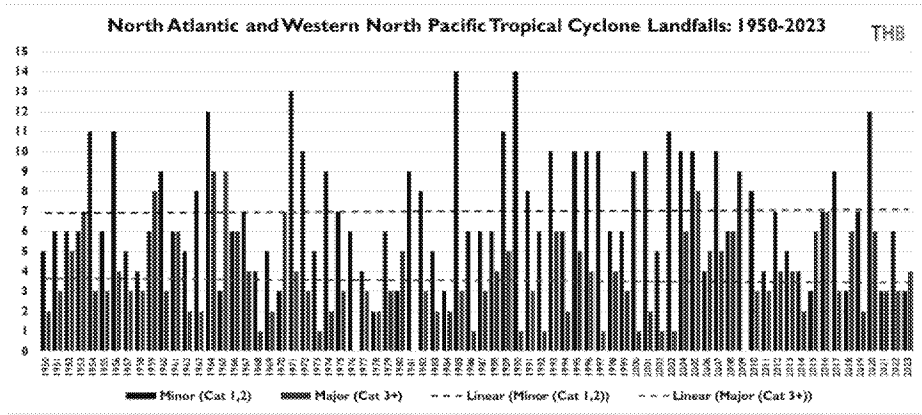


Figure 8.3.1 Tropical Cyclone Landfalls Source: [HYPERLINK "https://rogerpielkejr.substack.com/p/global-tropical-cyclones"] Weinko et al. (2012)

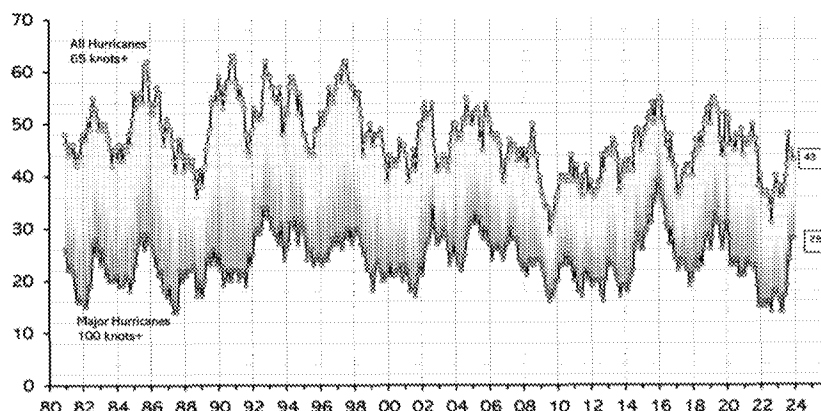
Similarly, after 1980, as shown in Figure 8.3.2, [Maue 2025, [HYPERLINK "https://climatlas.com/tropical/"]], shows that, which reproduces data from the Climate Atlas of Dr. Ryan Maue both neither all hurricanes and the total number of hurricanes nor the frequency of major ones hurricanes have not become more common since 1980, the period of rapidly growing human influences. In fact, indeed both numbers have trended down slightly since the 1990s:

Commented [A8]: Cite the Climate Atlas of Dr. Ryan Maue

Global Major Hurricane Frequency – 12 month running sums – @RyanMaue

Updated December 31, 2023

Last 30-years: 45.7 H | 24.4 M



Global Major Hurricane Frequency – 12 month running sums – @RyanMaue

Updated March 10, 2025

Last 30-years, annual: 45 H | 24 M

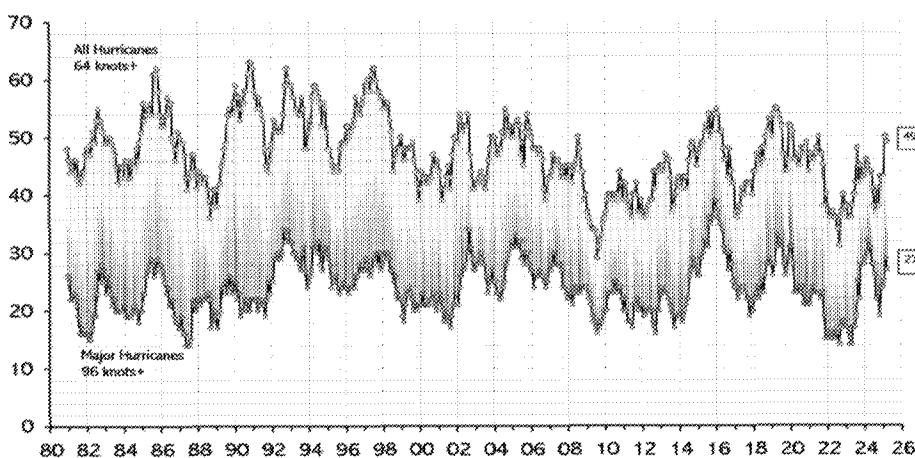


Figure 8.2.2: Global hurricane frequency. Source: Maue (2024/2025)

A metric that combines the number, duration, and frequency/strength of TCs is the Accumulated Cyclone Energy (or ACE) Index maintained at Colorado State University, shown in Figure 8.3.3. As is clear, it is also not clearly shows no long-term increase, in fact declining slightly and since 1990 has declined slightly.

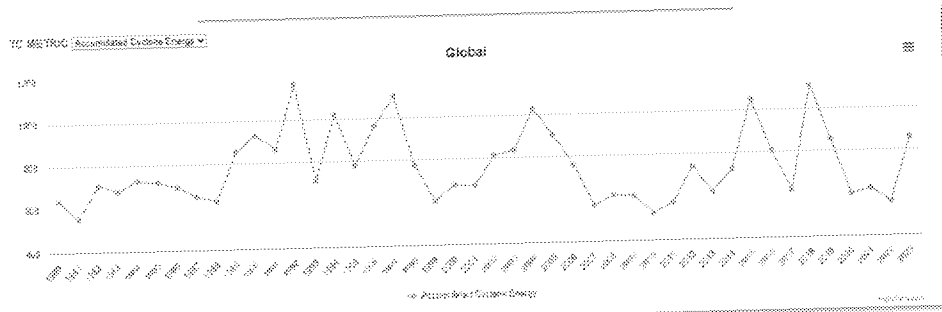


Figure 8.3.3: Global Accumulated Cyclone Energy. Source: Klotzbach (2025)  
[HYPERLINK "<https://tropical.atmos.colostate.edu/Realtime/index.php?arch&loc=global>"]

Note that Tu et al. (2024) report that the Power Dissipation Index (PDI), another different measure of the destructiveness of hurricanes that combines hurricane number, duration and strength, has either remained unchanged or has declined in all global oceanic basins since the mid-1990s. As is clear, it is also not increasing and since 1990 has declined slightly.

Today's global climate simulations are too coarse to project changes in TCs directly. Rather, projections are derived from finer "downscaled" simulations or proxies involving sea surface temperatures, winds, and aerosols. By these methods, a warming climate is expected to show climate models project declining hurricane formation rates, in a warming climate (Chand et al. 2022). Climate models also project fewer Tropical Cyclones under future global warming and even though models project they will increase in strength, the annual averages of rainfall maxima decline (Stansfield et al. 2020). Note that Tu et al. (2024) report that the Power Dissipation Index (PDI), a measure of the destructiveness of hurricanes, has either remained unchanged or has declined in all global oceanic basins since the mid-1990s.

#### 8.7.2.2.2 Wildfires

The IPCC has not provided an assessment of wildfires.

As shown in Figures 8.7.2.4.2.1 and 8.2.5 global wildfire activity as measured by European Space Agency peaked over a decade ago and shows a downward trend since this century.

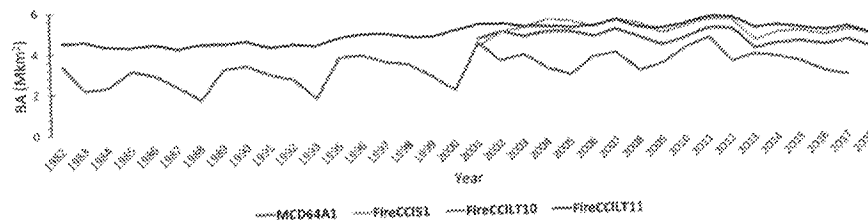


Figure 8.3.4: Global wildfire 1982-2018. Source: Copied from Oton et al. (2021). Note: the different coloured lines represent different data products based on satellites and algorithms used.

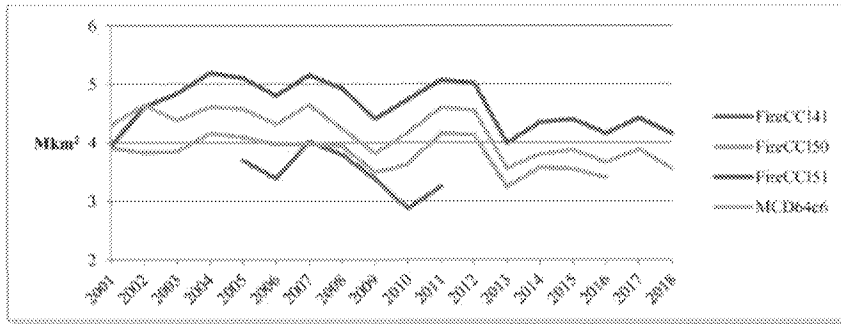


Figure 8.3.579.1: Global wildfire 2001-2018. Source: Copied from Lizundia-Loiola et al. (2021). Note: the different coloured lines represent different data products based on satellites and algorithms used.

US data from the National Interagency Fire Centre (NIFC) from 1926 to 2023 are shown in Figure 8.3.679.2.

Commented [A9]: I thought the trends were due to declining fires in the Amazon, masking any climate-related trend?

Commented [A10R9]: "global area burned appears to have overall declined over past decades, and there is increasing evidence that there is less fire in the global landscape today than centuries ago." Doerr and Santin, Proc Royal Society 2016

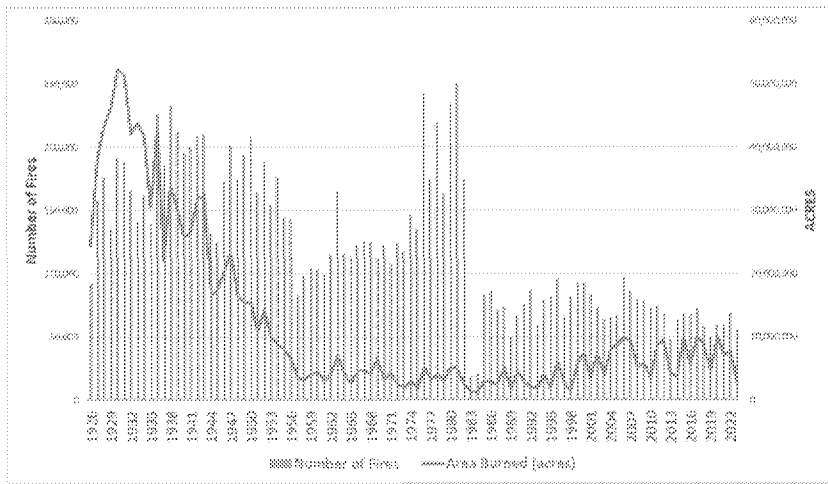


Figure 8.3.679.2: US wildfires 1926 to 2023. Source: National InterAgency Fire Centre data Pre-2017 (archived)

[<file:///C:/Users/Porter%20Hill/Dropbox/Brucehaven/Projects/DoE/Ross%20drafts/Pre-2017%20archived%20data/US%20wildfires%201926%20to%202017%20archived%20data.xlsx>] HYPERLINK

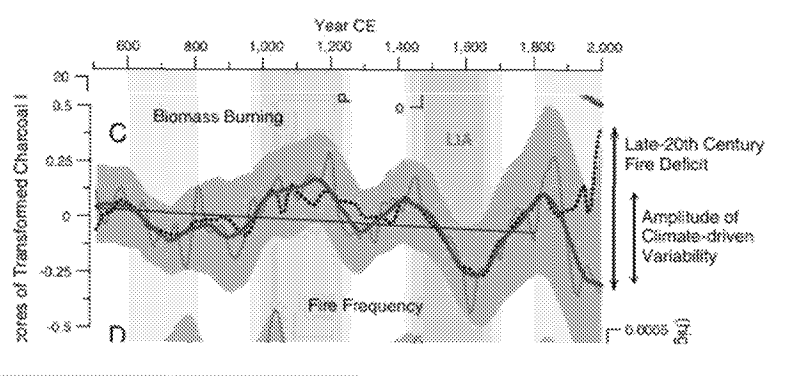
2017):%20https:\\web.archive.org\\web\\20200212033452\\https:\\www.nifc.gov\\fireInfo\\fireInfo\_stats\_totalFires.html" ]. 2018-2023: [ HYPERLINK "https://www.nifc.gov/fire-information/statistics/wildfires"]

Note the NIFC has removed the pre-1960 data from its current website. They claim it is because measurement methods changed after 1960. This explanation seems inadequate since agencies blend temperature and extreme weather data series in other contexts when measurement systems changed. In this case if anything the measurement of wildfires has improved since the early 20<sup>th</sup> century so any bias will be towards understating early wildfire counts. Nonetheless just focusing on the post-1985 interval the number of fires is not increasing. The area burned did increase but only until about 2007.

Forest fires have always been a part of nature, and they can certainly create conditions that are inhospitable in the short term for all life including humans. Science has confirmed the overall benefit and necessity of the occurrence of forest fires. While recent high-profile fires and seasons serve as a reminder of the potential destructive impact, the highest profile forest fire remains the 1910 Big Blowup fire which destroyed over three million acres including the elimination of entire towns like Taft, MT (Apple 2020). The 1910 fire reshaped the U.S. Forest Service (National Forest Foundation 2022) leading to a focus on fire suppression with a primary goal to defeat all forest fires (Forest History Society 2022). This led to the 10 am rule in 1935 that meant all fires spotted on any day had to be controlled by the following day at 10 am (National Forest Foundation 2022).

While defeating fire is certainly a noble goal, questions began to arise as to whether this behavior "followed the science" (US Forest Service 2022). Over time the U.S. Forest Service has begun to rethink its behavior, recognizing that new approaches such as prescribed burns, fuel elimination and controlled wildfires are more appropriate (Sonner 2016). Recent research is validating this approach and recognizing that more frequent smaller fires in forests likely result in the most healthy forests, water ecosystems and biodiversity (Stephens et al. 2021).

It is difficult to establish a natural baseline for wildfire activity because of active fire suppression activity since 1900. Paleoclimatic evidence indicates, however, that past wildfire activity was much higher than at present. Marlon et al. (2012) used sedimentary charcoal layers to reconstruct fire history of western US for the past 1400 years. They also fit a model to predict expected fire activity as a function of climatic conditions. The results are summarized in Figure ~~8.7.2.79.3~~ below (from Figure 2 in their paper).

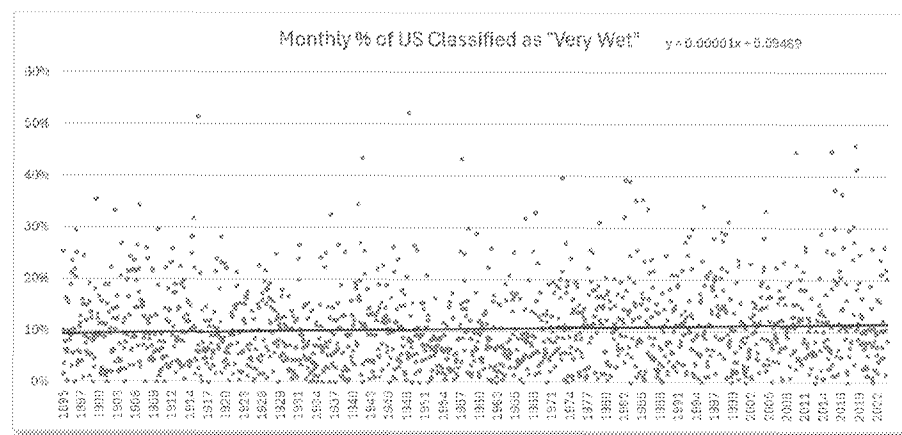


**Figure 8.7.379.37:** Fire frequency and fire deficit in the US. Source: Copied from Marlon et al. (2012)

In their figure the red line shows the smoothed charcoal record and the black dotted line shows the predicted charcoal record based on the statistical model. The gap at the end implies there has been a growing wildfire deficit over the 20<sup>th</sup> century. In other words, however much fire was observed in the 20<sup>th</sup> century it was less than what would have been observed in previous centuries based on the climatic conditions. Parks et al. (2025) likewise find that despite the recent increase in wildfire burn area in North America, a significant wildfire deficit remains relative to historical wildfire regimes there remains a significant wildfire deficit.

### 8.23.3 Precipitation

Figure 8.2.8 shows that US long term data from NOAA shows an insignificantly increasing tendency toward extreme wetness (-0.0001% per year)



**Figure 8.2.8:** Long term US wetness (%) Source: NOAA [HYPERLINK "<https://www.ncei.noaa.gov/access/monitoring/uspa/wet-dry/0>"]

Precipitation will be discussed further in the review of CONUS data below.

#### 8.23.4 Drought

As shown in Figure 8.3.9 US long-term data (NOAA) shows an insignificantly declining tendency toward extreme dryness (-0.001% per year)

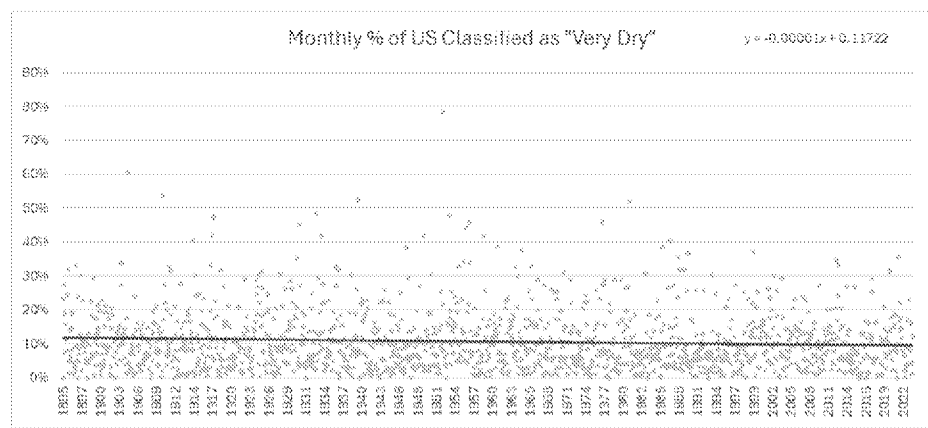


Figure 8.3.9: US dryness (%), 1895-2023. Source: NOAA [HYPERLINK <https://www.ncei.noaa.gov/access/monitoring/uspa/wet-dry/0/>]

Hogan et al. (2020) examines a 20-year high-resolution satellite-based drought measure and concludes that global drought has not intensified and is not connected to climate change. "It is possible to state firmly that global and main grain countries' drought areas and intensity trends have not been following global climate warming since 1980's."

#### 8.3.4 Analysis of Temperature and precipitation extremes in the Conterminous Contiguous US (CONUS) data on temperature and precipitation extremes

##### 8.3.4.1 CONUS daily temperatures are becoming less extreme

Daily maximum temperatures in the warm season (TMax, May-Sep) and daily minimum temperatures in the cold season (TMin, Dec-Mar) are available beginning in Dec-1898 (126 years). (The dataset consists of 1,211 CONUS stations designated as United States Historical Climate Network or USHCN stations (Quinlan et al. 1987, Karl et al. 1990). These stations were selected by NOAA as having the fewest problematic issues with gaps, station moves and instrument changes. Where gaps still exist, nearby stations (bias-corrected) were merged so that the median volume of data available for a station is 98%. Although there are certainly errors certainly reside in the dataset, with over

**Commented [A11]:** Again, I think we need a map of where the stations are; something like this one:  
[HYPERLINK [https://www.researchgate.net/publication/258660497\\_Uncertainties\\_Trends\\_and\\_Hottest\\_and\\_Coldest\\_Years\\_of\\_US\\_Surface\\_Air\\_Temperature\\_since\\_1895\\_An\\_Update\\_Based\\_on\\_the\\_USHCN\\_V2\\_TOB\\_Data/figures/fig=1](https://www.researchgate.net/publication/258660497_Uncertainties_Trends_and_Hottest_and_Coldest_Years_of_US_Surface_Air_Temperature_since_1895_An_Update_Based_on_the_USHCN_V2_TOB_Data/figures/fig=1)] More importantly, it needs to show how you've cut them up into regions



1,000 stations we can have relatively high confidence in any underlying signal we that might be discovered, can be characterized by relatively high confidence.

We begin with the question of whether the occurrence of daily record high or low temperatures changed has changed since Dec 1898. Each warm season has 153 days (1 May to 30 Sep) and each cold season has 122 days (1 Dec to 31 Mar). For each station and day, we calculated the year in which the record highest (lowest) temperature occurred. With 126 years of observations, if there were no temperature trends over time, the expected number of records for TMax would be 1.21 ( $=153/126$ ) per station per year and for TMin 0.96 ( $=122/126$ ) per station per year. Figure 8.4.10 indicates the observed distribution in time of the occurrence of these extreme events.

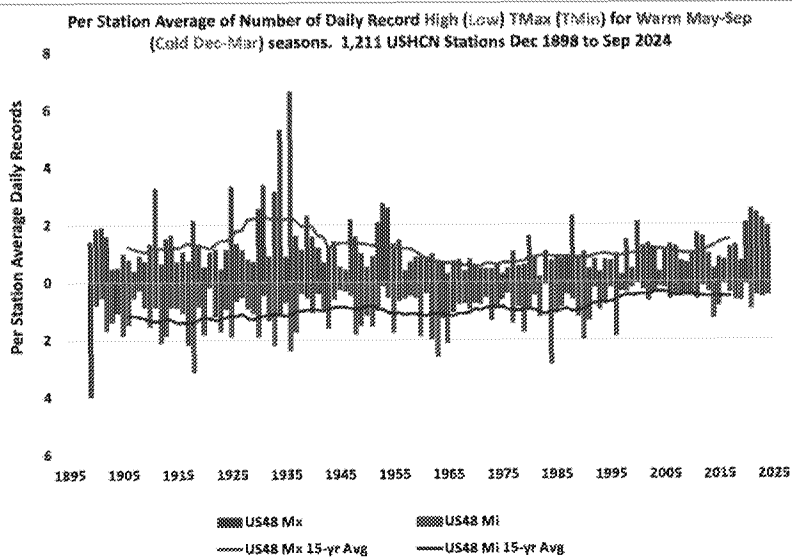
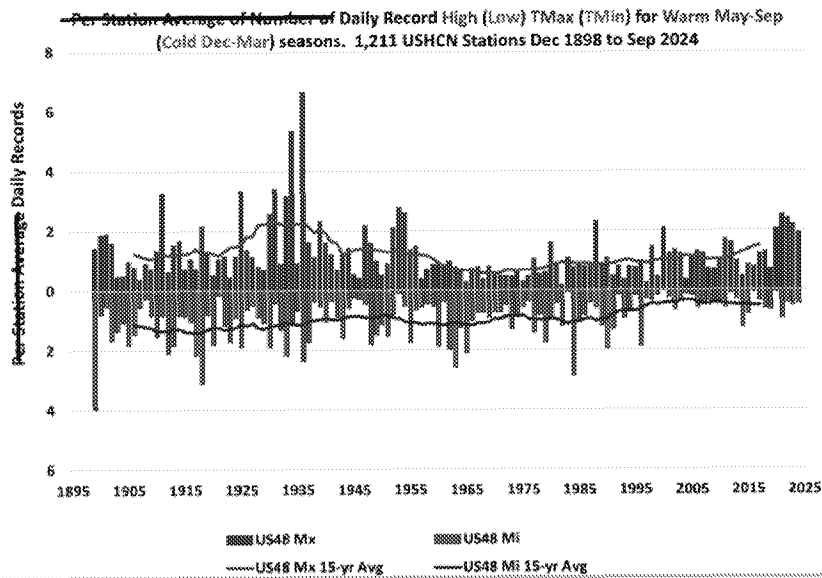


Figure 4.1.10 Number of daily record High (red) and Low (blue) for warm and cold seasons in the CONUS. The lines represent the 15-year running-centered average. Source: 1,211-USHCN stations supplemented as needed to achieve a minimum of 92% of observations in the 126-year period since Dec. 1898.

The results indicate a common feature in many metrics of warm-season extremes in the CONUS – the exceptional heat of the 1920s and especially the 1930s, peaking in 1936. On a per-station average, 60% of the TMax records and 59% of the TMin records occurred in the first half of the period (1899–1961).

On the cold side, the Valentine's Day Arctic outbreak in Feb. 1899 stands as the most extensive cold extreme experienced by the CONUS, with 1917–24. The frequency of cold records has declined, especially over the last quarter of the period in which only 13% of the extreme cold events were measured. In contrast, 35% of the extreme TMax records were achieved in the last quarter in accordance with statistical expectations. These general features have been noted in past assessments (IPCC AR5, IPCC AR6, NCA4, NCA5). Combining the two records the overall reduction in numbers of both cold and hot extremes over the past century indicates a climate less prone to extremes.

This pattern is also shown in Figure 8.4.2.1.1. For each station and for each year the hottest warm season and coldest cold season temperatures were calculated and converted to anomalies relative to the station's long-term warm and cold season (respectively) averages. Then the differences between these were computed by station and geographically averaged over all stations, thus yielding an annual measure of the expected range of local extreme temperatures for each year. Figure 8.1.1 shows the 15-year trailing average of this measure which has clearly declined over the past century.

**Commented [A12]:** Does this include a correction for varying station density? If not, it should just read "averaged".

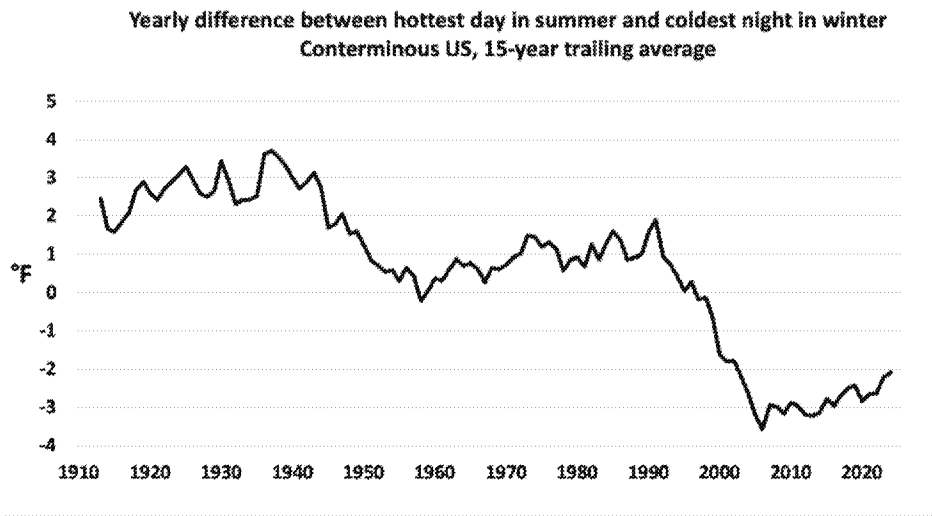


Figure 8.4.2.1.1—15-year trailing average of the difference each year of each station's hottest warm season TMax and coldest cold season TMin relative to the long-term average.

The average difference for each station between the hottest summer TMax and coldest winter TMin has declined about 5°F in the past 126 years. The decline is due mostly to warming winter TMin, but

a decline in the magnitude of summer TMax is also a factor. The rise in TMin has been strongly related to the growing presence of manufactured surfaces around the weather stations over the last 100+ years (Spencer et al. 2025).

Summarizing Figures 8.10.4.1 and 8.4.21.1, while temperature extremes are regularly experienced in the US and attract a great deal of media attention, long-term records show the US climate has become less extreme over time (milder), when measured in terms of the range between warm season maxima and cold season minima.

#### 8.24.2 Exceedances of a heat threshold

Under the heading of "The Risk of Temperature Extremes is Changing", the most recent US National Climate Assessment report (NCA5) notes the increase in a threshold metric of number of days at or above 95°F, stating:

*"The western US has been particularly affected by extreme heat since the 1980s ..., experiencing a larger increase in days over 95°F, as would be expected given the greater warming in that region relative to the eastern US. Several major heatwaves have affected the US since 2018, including a record-shattering event in the Pacific Northwest in 2021."*

Are the occurrences of 95°F days changing? In a climate as varied as that of CONUS, threshold statistics can be misleading. A region with many stations which ~~that~~ have near 95°F TMax average temperatures in the summer might see large swings in the metric when only small changes in average temperatures occur. Elsewhere with stations that either rarely or virtually always achieve 95°F TMax temperatures, a small change will not impact the results much at all. In the past 126 years, the average CONUS station experienced 129 days exceeding 95°F per 6-yr period, but the regional values range from 278 in the Southern Plains to 9 in the Northeast. Thus, one needs to view such threshold analyses with caution.

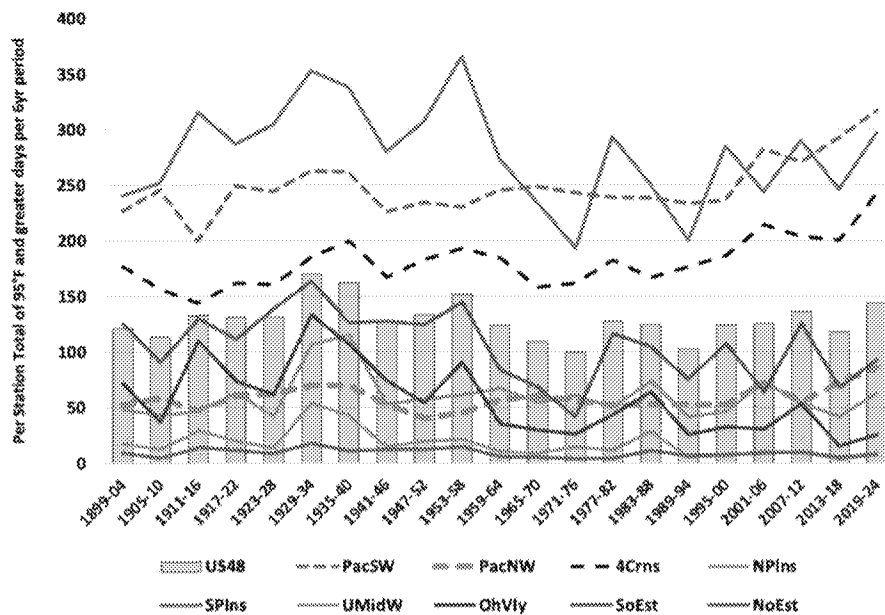


Figure 8.12.4.2. Total number of days  $\geq 95^{\circ}\text{F}$  in 6-yr periods, US 48 (bars) and regions (lines).

In Fig. 8.12.4.3, we see that only three of the nine regions, all in the West, have experienced upward trends in the number of  $95^{\circ}\text{F}$  or hotter days (dashed lines). The CONUS as a whole has not and the other six regions have experienced declines.

The Pacific NW heatwave of 2021 is referenced as supportive information for of the NCA5 claim: an event we examined more closely in Section 6.4. The evidence indicates it was a “black swan” event, i.e., a single, unprecedented event in the existing record, not part of a suggesting it is not indicative of a pattern of increasing extreme heat. For example, the 5-day average tropospheric grid-point temperature anomaly over the Pacific NW during that event was  $+10.0^{\circ}\text{C}$ , the most extreme NW grid point summer anomaly in the 46 years from over 4 million grids. In contrast, the global anomaly during that time was virtually zero ( $+0.03^{\circ}\text{C}$ , Mass et al. 2024).

The heading “The Risk of Temperature Extremes is Changing” suggests positive trends are now being observed in threshold temperatures on a widespread basis, but that is not evidenced in the combined CONUS results of the figures above.

### 8.34.3 Heatwaves

Heatwaves (consecutive days that exceed an extreme threshold) have a greater societal impact than Of more impact than a single daily record. We measure is the phenomena of heatwaves, or consecutive days which exceed an extreme threshold. For this study, the metric will be the number of “Heatwave Days” here defined as the sum count of all days in May-Sep each year which that exceed

the 90<sup>th</sup> percentile and that occur lie within consecutive periods a run of at least six consecutive days in length. This is equivalent to the method used in NCA5 except that the reference period here is the entire record 1899-2024 while NCA5 limited truncated the reference period to 1961-1990, a cool episode time. By selecting 1961-1990, the truncation occurrence of (happens) positive results (days exceeding the 90<sup>th</sup> percentile) will be enhanced in periods warmer than the reference base period, especially if starting in 1960 and moving to the present (see *Urban Influences* below).

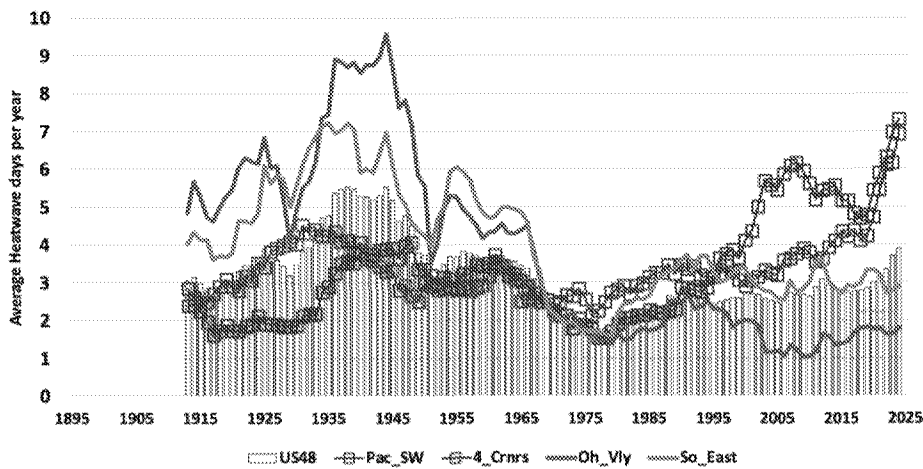


Figure 8.13 4-15-year trailing average of number of heatwave days per year per station in the CONUS (bare) and four regions: Pac\_SW (purple squares, CA, NV), 4\_Cnrs (red squares, AZ, NM, UT, CO), Oh\_Vly (blue, MO, IL, KY, TN, IN, OH, WV) and So\_East (green, MS, AL, GA, FL, SC, NC, VA).

Figure 8.13 4.4 indicates again the excessive heat of the first half of the 20<sup>th</sup> century, primarily in the eastern two-thirds of the nation, as seen in the regional values for the Ohio Valley and the Southeast as examples. The West has seen a recent increase of heatwave days and the two regions with the highest number are shown, the Pacific Southwest and the Four Corners (NCA5). This indicates that the background warm season circulation favored heatwaves in the eastern portions of the country in the first half of the 20<sup>th</sup> century, but in the 21<sup>st</sup> century the patterns have favored heatwaves in the West. For CONUS as a whole, heatwaves are no more common today than they were a century ago.

Of interest here is the regional variation of this metric. The four northern regions (Pacific NW, Northern Plains, Upper Midwest, and Northeast) on average experience 15 to 27 heatwave days per 15-year period. In contrast, the five southern regions (Pacific Southwest, 4-Corners, Southern Plains, Ohio Valley and Southeast) see 37 to 54 such days, essentially twice as many. This suggests the summer circulation pattern is more prone to stationary events in the southern regions while transient systems in the northern regions are more common and thus cut short these potentially longer events.

#### Urban influences

The NCA5 directs readers to the website [HYPERLINK "https://www.globalchange.gov/indicators/heat-waves"] (USGCRP 2023) to view the number of urban heatwaves by decade from the 1960s. The figure reveals shows a monotonic increase in each decade from 2 occurrences per year in the 1960s to 6 in the 2020s. The definition of a heatwave is an unusual but practical measure from a human discomfort perspective—a period of at least 2 consecutive days when the minimum apparent minimum temperature (combination of temperature and humidity) exceeds the 85<sup>th</sup> percentile. Note too, the dataset is limited to the 50 largest U.S. cities in the US.

These increasing values since 1960 presented in USGCRP (2023) are entirely reasonable, but are unrelated to GHG emissions for at least two reasons unrelated to GHG emissions. Urbanization in these cities is a major factor in the rise of TMin relative to co-located TMax and relative to TMin at rural stations. Also, the 1960s was the coldest decade and 1970s the second coldest decade since the 1910's, so this starting date preconditions the time series to show increases. This does not diminish the real rise in nighttime temperatures in major U.S. cities and the societal impacts associated with these changes. However, we note for a variety of reasons, that summer TMax (especially in rural areas) serves as better response variable for detecting potential changes in heatwaves influenced by changes in the background climate due, for example, to increasing GHGs (Christy et al. 2009). For the CONUS as a whole, the evidence in this section suggests GHG emissions have had little to no effect on heatwaves in the CONUS.

#### 8.3.4.4 Extremes in daily precipitation.

Because precipitation involves a discrete phase change (water vapor to liquid), it is due to its stochastic and episodic in character and therefore precipitation requires careful statistical treatment to understand variability over long time periods (see 8.1 Introduction). The US National Climate Assessments (NCA4, NCA5) have highlighted an increase in the occurrence of the heaviest precipitation events (defined in different ways) primarily in the eastern half of the CONUS, especially the Northeast, when starting in either 1901 or 1959. Interestingly, the regional variations indicate that the largest increases in extreme events are in the Northeast and least the smallest in the West, which is a trend counter to the changes in temperature extremes shown above.

McKrick and Christy (2019) examined long-term and consistent station observations of daily precipitation to test some of these NCA claims for the Southeast and West Coast. In neither case when the time series were extended back in time (as far as 1872 in some cases) or when starting later (1978), there were no were the trends significant trends for either region. For this report we updated these findings with similarly constructed observations from 29 stations on the Pacific Coast (1893ff from San Diego, CA to Blaine, WA, see Figure 8.14), 24 stations in the humid Southeast (1872ff from Austin, TX to Washington, DC, see Figure 8.15), and 21 stations in the Northeast (1888ff from Buffalo, NY to Gardiner, ME, see Figure 8.16). The results were as follows:

##### Pacific region:

- .....Average precipitation trend is significant (downwards) in Astoria, insignificant elsewhere.
- .....The trend in rainfall variance is positive and significant in Big Sur, insignificant elsewhere.
- .....The trend in daily maximum precipitation is positive and significant in Aberdeen and Big Sur and negative and significant in Newport (insignificant elsewhere).
- .....Averaged over all stations in the region none of these three trend parameters is statistically significant.

##### Southeast region:

**Commented [A13]:** Stochasticity and LTP are really different things, but we somehow conflate them in this sentence. Or am I missing something?

**Commented [A14R13]:** By removing the 'therefore' I think we are now not conflating them.

- .....The trend in average precipitation is positive and significant in Mobile and Qulman, insignificant elsewhere.
- .....The trend in rainfall variance is positive and significant in Mobile, insignificant elsewhere.
- .....The trend in daily maximum precipitation is positive and significant in Vicksburg and Norfolk, insignificant elsewhere.
- .....Averaged over all stations in the region none of these three trend parameters is statistically significant.

#### Northeast region:

- .....The trend in average precipitation is positive and significant in 9 of 21 locations and in the region averaged overall.
- .....The trend in rainfall variance is positive and significant in Portland, Albany and Buffalo, insignificant elsewhere.
- .....The trend in daily maximum precipitation is positive and significant in Portland and Gardiner, insignificant elsewhere.
- .....Averaged over all stations in the region the trend parameters for variance and maximum precipitation are not statistically significant.

In the Pacific region, over the whole sample, the trend in average precipitation trends downward, being significant only is negative and significant in Astoria, and insignificant elsewhere. The trend in rainfall variance increases, is positive and significant only in Big Sur, and insignificant elsewhere. The trend in daily maximum precipitation is positive and significant in Aberdeen and Big Sur and negative and significant in Newport and insignificant elsewhere. Averaged over all stations in the region none of these three trend parameters is statistically significant.

In the Southeast region over the whole sample the trend in average precipitation is positive and significant only in Mobile and Qulman, the trend in rainfall variance is positive and significant only in Mobile and the trend in daily maximum precipitation is positive and significant only in Vicksburg and Norfolk. Averaged over all stations in the region none of these three trend parameters is statistically significant.

The Northeast region exhibits a pattern of increasing average rainfall. The trend in average precipitation is positive and significant in 9 of 21 locations and in the region averaged overall. The trend in rainfall variance is positive and significant only in Portland, Albany and Buffalo and insignificant elsewhere and not in the regional average. The trend in daily maximum precipitation is positive and significant only in Portland ME and Gardiner ME and insignificant elsewhere and not in the regional average.

**Commented [A15]:** Suggest a simple table summarizing these trends.



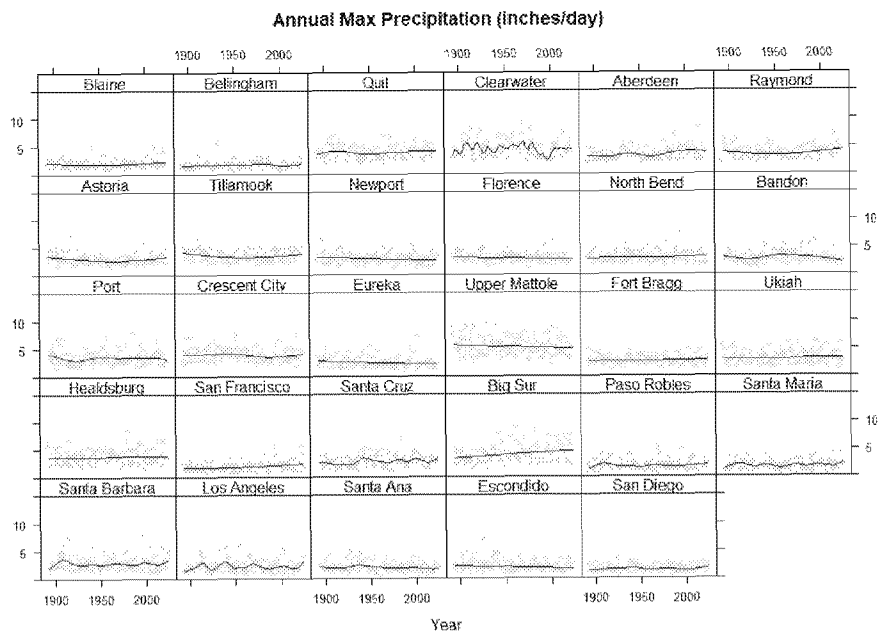


Figure 9.11 Annual maximum precipitation for 20 Pacific stations 1900 to present

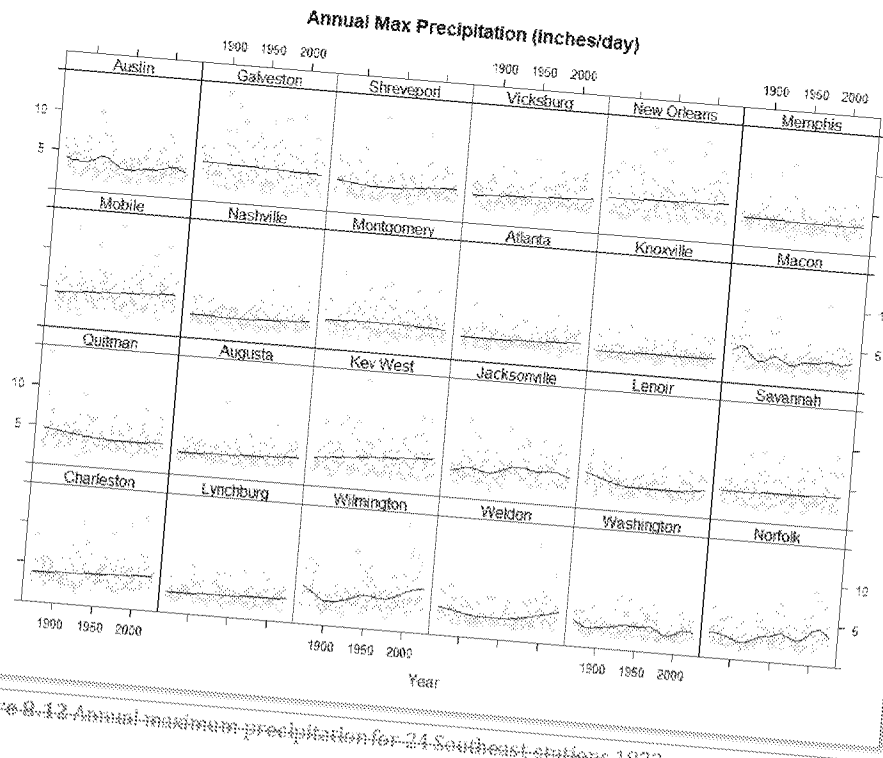


Figure 8-12 Annual maximum precipitation for 24 Southeast stations 1872 to present

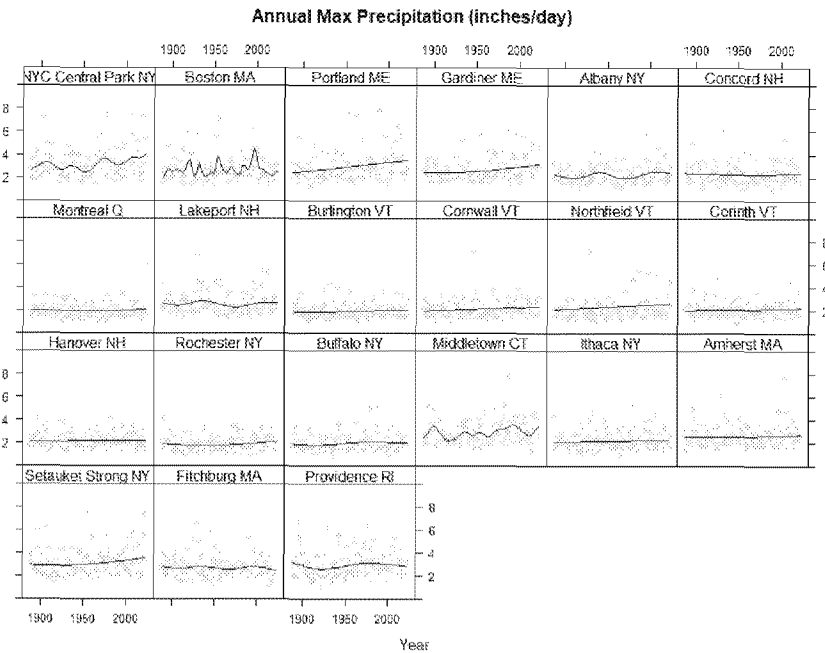


Figure 9.13 Annual maximum precipitation for 21 Northeast stations 1898 to present

#### Pacific Coast heavy rainfall events

The Pacific Coast receives considerable amounts of precipitation from Atmospheric River (AR) events which often last more than a day or two (e.g., Gershunov et al. 2017, Pan et al. 2024). The worst known such event in recent history was the Ark Storm that occurred between December 1861 and January 1862, which dumped nearly 10 feet of rain in parts of California and submerged the entire Central Valley for weeks under as much as 15 feet of water (Brewer 1930, Nall and Halbert 2007). Paleoclimate research has found six megastorms more severe than 1861–1862 in California during the last 1000 years, occurring at intervals of 300 years or so (Porter et al. 2011).

#### SIDEBAR: Perils of short data records

San Francisco provides a good case study of the limitation of using short historical samples to characterize natural variability of extreme events. Suppose we use a 130-year sample of daily San Francisco precipitation from 1895 to 2024 and we look for 3-day, 5-day, 14-day and 30-day rainfall records. The results are as shown in Table 9.12.

| Event  | Record (inches) | Year |
|--------|-----------------|------|
| 3-day  | 6.94            | 2023 |
| 5-day  | 8.55            | 2023 |
| 14-day | 12.62           | 2023 |

Table 8.12: Extreme rainfall records, San Francisco, 1895-2024.

The records all cluster in the more recent data—2023 appears to be an exceptional year and since it is near the end of the sample it would might point to the possibility suggest that the climate has shifted into a potentially more hazardous state, perhaps as a result of human influences.

But the picture is very different if we use a sample that begins 45 years earlier, in 1950. If we extend the record back to 1950 the picture changes. Table 8.2.3 shows that the record-setting events then all happened in the 1860s. Furthermore 2023 is now not even in 2<sup>nd</sup> place but falls to 3<sup>rd</sup> or 4<sup>th</sup>. Also, comparing the records of the two charts the extreme precipitation events in 1862 and 1867 involved considerably more rainfall than the 1992 and 2023 events, with 14- and 30-day totals about 50 percent higher.

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| Event  | Record (inches) | Year | Rank of 130-yr.<br>extreme |
|--------|-----------------|------|----------------------------|
| 3-day  | 8.65            | 1867 | 3                          |
| 5-day  | 9.60            | 1867 | 3                          |
| 14-day | 19.05           | 1862 | 4                          |
| 30-day | 28.25           | 1862 | 2                          |

Table 8.23: Extreme rainfall records, San Francisco, 1850-2024.

The The characterization of the range of natural variability is made even more remarkable when paleoclimate evidence is examined. Porter et al. (2011) discovered that in the past 1,900 years at least six megastorms were more intense than the devastating 1861-62 ArkStorm that struck the region. Thus, evidently such extreme events have impacted the region about every 300 years, though not since 1895.

This example illustrates the limitations of using relatively short climate periods (~130 years) to assess the character and range of natural variability in general and of extreme events in particular. Accurate representation of the full range of natural variability is necessary for any attribution analyses (see 6.4): infrastructure planners, emergency management institutions and attribution scientists would understand the significant mischaracterization of the magnitude of a future extreme if based only on the last 130 years. In this case, a single time sample of 130 years provides an underestimation of the extreme value by up to 50% determined when adding only 45 more years of observations. Compared to millennial-scale paleoclimate evidence, an even greater underestimation would occur. An important lesson is that the climate can deliver great surprises on its own even without human influences.

We examine occurrences of 5-day deluges as follows. In a 130-year span there are 265-year intervals. At each location we computed the 5-day precipitation totals throughout the year and selected the 26 highest values. A single year may have more than one of the 26 heaviest. Each of these can be thought of as 1-in-5-yr events. If there are no trends in precipitation then the total number of these events across all stations should be evenly spread out on an annual basis over the years. In Fig. 8.14.4.5 we show the distribution in time of these events. The deluges associated with the massive 1997-99 El Niño event are readily apparent. While erratic, as is typical of these types of precipitation metrics, there is no indication of a tendency to become more frequent over time.

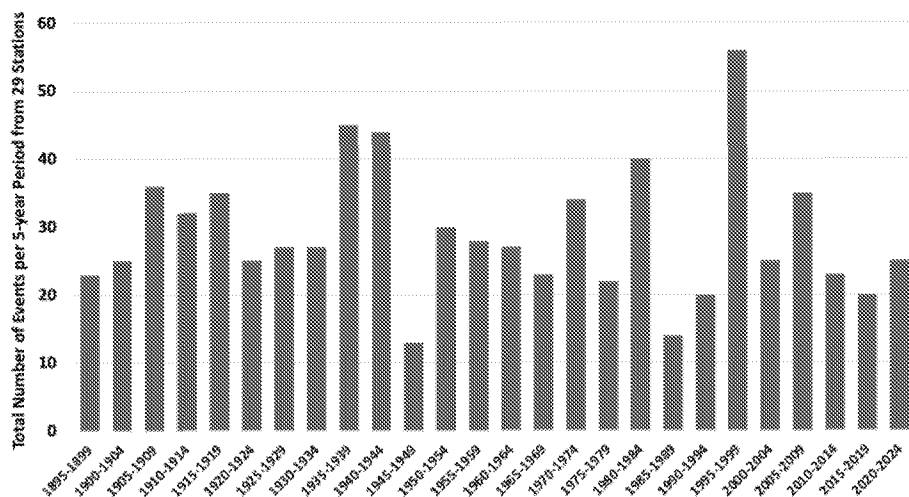


Figure 8.144.5 The time distribution by 5-year periods of the 26 heaviest occurrences for each station (i.e., nominal 1-in-5 year event).

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#### Southwest heavy rainfall events

The temporal pattern of 5-day totals of the 1-in-5yr heavy events in the humid Southwest (Figure 8.154.6) is generally unremarkable, though a cluster of higher values appears in 1995 to 2019. The increase in those years is due largely to the 4 northeastern-most stations of Wilmington NC, Weldon NC, Washington DC, and Norfolk VA. This confirms the pattern indicated in NCA4 and NCA5 of a tendency for an increasing frequency of heavy events, due to a temporal clustering of tropical storms from eastern NC to Maine discussed below. Otherwise, the remaining 20 stations show an unremarkable temporal distribution of heavy events.

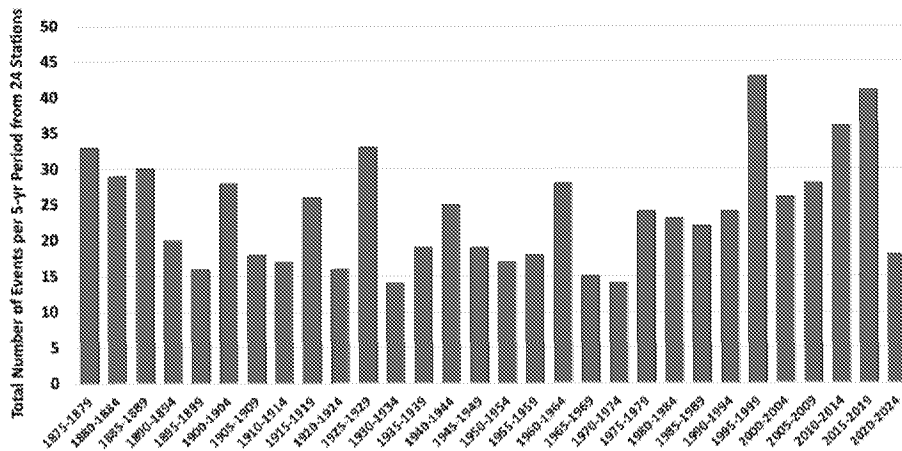


Figure 8.154.6. As above but for the 30 heaviest 1-in-5-yr events for 24 stations in the humid Southeast from Austin, TX to Washington, DC in 5-year bins for 1875-2024.

#### Northwest heavy rainfall events

Fig. 8.16.4.2 shows the 27 (1-in-5-yr) heaviest 3-day events for the last 135 years in 21 stations in the Northeast (including Montreal, Canada). We use 3-day totals here as this produced the largest variations in time. In this region, 72% of the events occur during June to October and are dominated by tropical incursions of hurricanes, tropical storms or tropical storms that transition to extratropical systems. According to NCA4 and NCA5 this region experienced the largest increases in extreme events, so it shall be examined more closely.

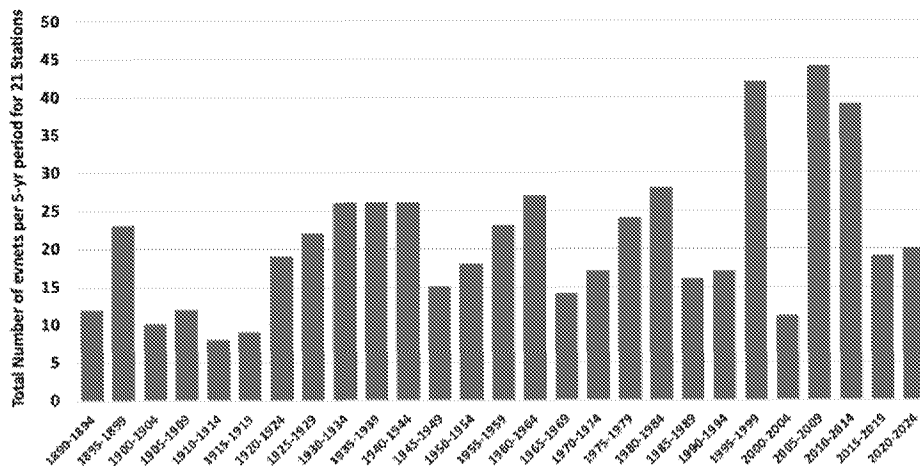


Figure 8.16.4.7. Time distribution of the heaviest 27 (1-in-5-yr) heaviest 3-day precipitation events for 21 stations from NY to ME, including Montreal.

Howarth et al. (2019) report differences in the Northeast between two 18-year periods: 1979-96 and 1997-2014 (a similar region as in Fig. 8.16 that includes PA and NJ) of various precipitation extremes. One metric which indicated a dramatic increase (317%) was found for 24-hr events  $\geq 6$  inches. This high increase is due to the very small numbers of such events of which there were only 6 in the first period and 25 in the second as reported for 58 stations. This high percentage increase is due to the very small numbers of the events; only 6 in the first period and 25 in the second. Most of the stations did not record such an event suggesting these erratic, episodic events over brief, 18-yr periods, need scrutiny by additional statistical methods.

Using the information in Fig. 8.16.4.7 over the same years as Howarth et al. we find a 51% increase in the frequency of heavy events between the two periods. One can see in Fig. 8.16 that it was unfortunate that Howarth et al. ended in 2014 prior to a return to the long-term average of such events.

A feature of Howarth et al. is the use of single day totals which is questionable because extreme events are often spread across the time of observation boundary. Thus stations measuring at 0700 LT versus those at Midnight will have differing results for a particular event which would then have major impacts on counting these events. We use the 3-day totals in Fig. 8.16.4.7 to be sure to capture the extent of these extreme downpours. In any case, we can confirm that the period 1997 to 2014 experienced a cluster of heavier events as Howarth et al. have documented.

Howarth's most remarkable claim (317% increase in 6" days) is potentially misleading because it is a threshold statistic (see Section 8.3.4.2 above) and a ratio of small numbers over a short period. The result is not representative of relative extreme events for the whole region since the majority of stations never experienced a 6" total. Fig. 8.16 above determines the same number of events for each station (27 heaviest events) whose heaviest values ranged from 4.4" to 12.5" and their 27<sup>th</sup> heaviest values ranged from 3.3" to 5.0". This analysis thus allows each station to be equally represented. In

other words, if there is a region-wide increase in heavy events, it should be seen in the sum of all stations. Note too that the period of record here is 135 years vs. 36 years of Howarth et al. Except for three 5-year periods between 1995 and 2014 there is nothing statistically remarkable about the results in Fig. 8.164.2.

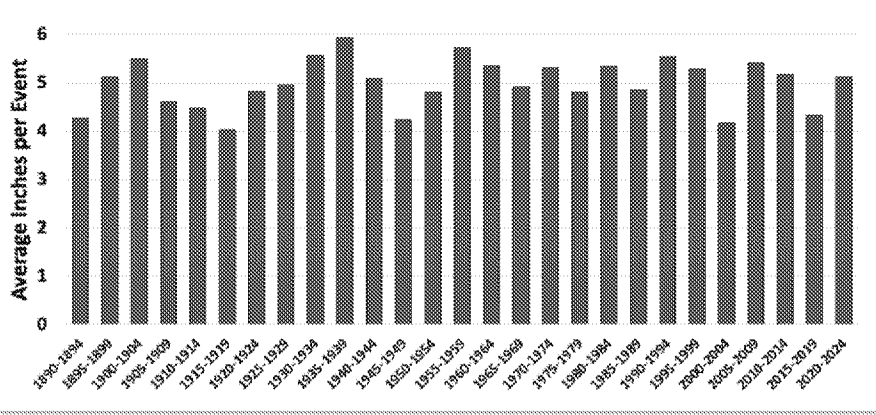


Figure 8.174.8. Average amount of precipitation falling in the 1-in-5yr events for the NE stations.

An interesting aspect of Northeast precipitation is that there has been no change in the amount of precipitation per heaviest event, as shown in Fig. 8.174.8. The trend is only +0.02"/decade. The highest amount, 1935-39, includes the Great New England Hurricane of 1938, one of the rare major (Category 3 or higher) hurricanes to strike the region. The results in Figs. 8.4.615 and 8.16.4.7 suggest that though there was an uptick in the number of events during the period 1995 to 2014, the events, individually, are not becoming more intense.

Jong et al. (2024) document the increase of tropical influences on precipitation events in the Northeast since 1959 and concluded, "The autumn extreme precipitation trend over the Northeast US is primarily attributed to tropical cyclone-related events since the 1990s." The question then becomes, was the temporal clustering of tropical systems in 1997-2014 which affected the Northeast a response to increasing GHGs? Jong et al. examined CMIP-6 model output which suggests that there will be fewer such systems in the 21<sup>st</sup> century but that the intensity of the rainfall events might increase. This conjecture is not seen in Fig. 8.17 where the amount per event has remained steady over the 135-year period.

For substantial urban areas there is some evidence to indicate the heaviest rainfall events may be redistributed due to the impact urban infrastructure has on the local weather (e.g., Pielke Sr. et al. 2011; Zhang et al. 2018; Yang et al. 2024). Yang et al. state, "Cities that experience compact development tend to witness larger increases in extreme rainfall frequency over downtown than their rural surroundings, while the anomalies in extreme rainfall frequency diminish for cities with



dispersed development.” While this is an important insight to consider, the effect on the specific stations used in this analysis is unknown, or at least not detectable in Fig. 8.1.7.

In summary, the evidence from the historical record of extreme precipitation events in the CONUS is generally not consistent from region to region so that inferences regarding trends and their projections are wrought with significant uncertainty. In most regions and perhaps all, it is our opinion that the very nature of the erratic and episodic character of extreme precipitation events renders the discovery of statistically significant changes, including a relationship to CO2 concentrations, a recult yet to be achieved (McKinnick and Christy 2019).

## 8.7.4§10 Summary

To be inserted

Based on the content provided in the document, here are the five most important takeaways:

- Limited Detection of Anthropogenic Signals: The IPCC has asserted high confidence in detecting an anthropogenic signal in only 4 out of 34 weather impact categories, and medium confidence in 4 more. For the remaining 26 categories, no anthropogenic signal is claimed to be detected.
- Slow Emergence of Trends: Even under the most extreme forcing scenario (RCP3.5), the IPCC expects very few anthropogenic trends to emerge within this century for most weather impacts.
- Natural Variability Dominance: Natural variability continues to dominate patterns of extreme weather systems. Simple assertions of trend detection are often complicated by regional heterogeneity and trend reversals over time.
- RCP3.5 Scenario Implausibility: The document notes that the RCP3.5 scenario is described as an implausible high-end storyline, not a “base case” or “business-as-usual” projection.
- Conflicting Messages on Attribution: The document mentions that AR6 (IPCC Sixth Assessment Report) offers conflicting messages about the attribution of extreme weather to anthropogenic causes, highlighting the complexity and uncertainty in this area of climate science.

These takeaways emphasize the nuanced and complex nature of attributing extreme weather events to climate change, and the importance of considering natural variability and uncertainty in climate projections.

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## Appendix: Review of IPCC and NCA Findings on Extreme Weather

The sources we review will be denoted as follows:

**SREX:** The IPCC *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (2012)

**AR5:** The IPCC *Fifth Assessment Report Working Group I* (2013).

**AR6:** The IPCC *Sixth Assessment Report Working Group I* (2021).

**NCA17:** The *US Climate Science Special Report of the Fourth National Climate Assessment* (2017) Volume I Chapter 6.

### 8A.1 Overview: IPCC Assessment of signal emergence in extreme weather types (AR6 WG1 Table 12.12)

Table 8A.1 reproduces the findings of AR6 Table 12.12 which indicates, for 34 major weather event and impact types, whether a signal of anthropogenic forcing has been detected in the historical record (column 1), whether such a signal is likely to emerge by 2050 under the extreme RCP8.5 scenario (column 2) and whether it is likely to emerge by 2100 under RCP8.5 forcing (column 3). It should be borne in mind that the latter two columns suffer from the deficiencies of GCMs discussed in Chapter IX. And as we discussed in Ch X on attribution, AR6 offers three conflicting messages within the AR6 regarding about attribution of extreme weather. Nevertheless, we provide this Table is provided here for reference.

Several patterns stand out. First, detection of an anthropogenic signal is asserted with *high confidence* in only four out of the 34 weather impact categories an anthropogenic signal is asserted with *high confidence* in only four, and with *medium confidence* in a further four. For the rest, the IPCC does not *NOT* claim to have detected an anthropogenic signal in the remaining 26 categories. Of the four *high confidence* assertions, two are for changes in average temperatures (air and ocean), which hence are not measures of extreme weather. Also two further, two of the four *medium confidence* assertions are related to ocean chemistry and thus are likewise not related to extreme weather. The IPCC does not *NOT* assert a detectable human influence on many non-temperature weather features such as wind, precipitation, flooding, and drought, etc.

Second, as shown in, columns 2 and 3 show that the IPCC expects very few such anthropogenic trends/signals to emerge within this century, even under the most extreme forcing scenario. As we discuss in Section 4.2 the RCP8.5 scenario is an implausible high-end storyline, it is not a “base case” or “business-as-usual” projection. Yet even still, even so, most weather impacts are not expected to exhibit *show* an anthropogenic signal this century. As will be clear from the underlying report text, natural variability dominates patterns of extreme weather systems and simplistic assertions of trend detection are frequently undermined by regional heterogeneity and trends reversals over time.

| Climate Impact Driver Type | Climate Impact Driver Category | Already emerged in the Historical Record <sup>1</sup> | Emerging by 2050 in Most Extreme CO <sub>2</sub> Emissions Scenario <sup>2</sup> | Emerging by 2100 in Most Extreme CO <sub>2</sub> Emissions Scenario <sup>3</sup> |
|----------------------------|--------------------------------|-------------------------------------------------------|----------------------------------------------------------------------------------|----------------------------------------------------------------------------------|
| Heat & Cold                | Average air temperature        | YES in most regions                                   | YES                                                                              | YES                                                                              |
|                            | More heat extremes             | YES in most regions                                   | YES in land regions                                                              | YES                                                                              |
|                            | Fewer cold extremes            | YES in a few regions                                  | YES in many regions                                                              | YES                                                                              |
|                            | Less frost                     | NO                                                    | NO                                                                               | NO                                                                               |

|              |                                         |                          |                       |                       |
|--------------|-----------------------------------------|--------------------------|-----------------------|-----------------------|
| Water & Dry  | Average-precipitation-inches-per-decade | NO                       | YES (less) YES (decr) | YES (less) YES (decr) |
|              | River-flooding                          | NO                       | NO                    | NO                    |
|              | Heavy-precipitation-causing-floods      | NO                       | NO                    | YES in a few regions  |
|              | Land-slides                             | NO                       | NO                    | NO                    |
|              | Aridity                                 | NO                       | NO                    | NO                    |
|              | Hydroelectric-power                     | NO                       | NO                    | NO                    |
|              | Agricultural-irrigation-increased       | NO                       | NO                    | NO                    |
| Wind         | Fire-weather                            | NO                       | NO                    | NO                    |
|              | Average-wind-speed                      | NO                       | NO                    | NO                    |
|              | Severe-wind-storms                      | NO                       | NO                    | NO                    |
|              | Tropical-cyclone                        | NO                       | NO                    | NO                    |
| Snow and Ice | Sand-and-dust-storms                    | NO                       | NO                    | NO                    |
|              | Snow-glacier-retreat                    | NO                       | YES in a few regions  | YES Arctic snow       |
|              | Roads/cracks                            | YES                      | YES                   | YES                   |
|              | Lake-&-river-ice                        | NO                       | YES                   | YES                   |
|              | Arctic-sea-ice                          | YES                      | YES                   | YES                   |
|              | Antarctic-sea-ice                       | NO                       | YES                   | YES                   |
|              | Heavy-snowfall-and-ice-storms           | NO                       | NO                    | NO                    |
|              | Hail                                    | NO                       | NO                    | NO                    |
|              | Snowmelt/ice                            | NO                       | NO                    | NO                    |
|              | Relative-sea-level                      | NO                       | YES                   | YES                   |
| Coastal      | Coastal-flood                           | NO                       | NO                    | NO                    |
|              | Coastal-erosion                         | NO                       | NO                    | NO                    |
|              | Coastal-inundation                      | NO                       | NO                    | NO                    |
| Open Ocean   | Average-ocean-temperature               | YES                      | YES                   | YES                   |
|              | Marine-ecosystems                       | NO                       | NO                    | NO                    |
|              | Ocean-acidity                           | NO                       | YES                   | YES                   |
|              | Ocean-salinity                          | YES                      | YES                   | YES                   |
| Other        | Dissolved-oxygen                        | YES (Pacific & S. Ocean) | YES                   | YES                   |
|              | Air-pollution/weather                   | NO                       | NO                    | NO                    |

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*(RM May 13 edits: Inserted Judy's new Sec 8.3 + wildfire text, John's revised Fig 8.4.2 short text in place of Table 8.2.1.)*

*(IRC edits May 14: folded the results from the three precipitation extremes from Ross's analysis into each of the already-discussed sections, minor edits)*

*(IC light edits May 14)*

## **78 Extreme weather in the US and elsewhere**

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### **78.1 Introduction**

High impact weather extremes, usually related to temperature, and/or precipitation, and/or excessive wind, often can disrupt infrastructure and therefore endanger human health and thriveability/wellbeing. Indeed, the ability of any surface-dwelling species to live productively is somewhat constrained by these extremes which in essence create the bounding limits for survival. The issue is not whether extremes occur, for they are intrinsic to the chaotic climate system. Rather, it is whether there are long-term (decadal scale) changes in the frequency and/or character of extremes ("detection"), as well as the extent to which such changes here is whether these extremes, and their attendant changes in potential danger hazards, may be changing and if so whether the change is in response caused by anthropogenic emissions increases in infrared-absorbing of greenhouse gases (GHGs) ("attribution"). (e.g., IPCC AR6 Seneviratne et al. 2021).

It is naïve to assume that any recent unprecedented extreme event observed recently is caused by human influences on the climate. Unfortunately, that's that assumption is wrong in two ways. First, climate is about the statistical properties of weather over decades, not single events. And second, there are only about 130 years of the reliable. Unfortunately, observational records that can be analyzed statistically extend back only for the sample of time from which we are able to quantitatively analyze variations in extreme events is quite brief, about around 130 years. That brief interval does not. This period certainly does not begin to contain all of the extreme events that the climate system is able to create naturally on its own. Over geologic time the climate system has generated an (essentially) infinite variety of weather patterns and extremes which that humans have never observed, and thus do not enter our are absent from the databases from which used to determine extreme statistics. are determine d. [see *Perils of short data records* below]. Thus, assuming that a for that reason, attributing climate pattern or an extreme event hitherto unprecedented in the record not experienced in our lifetime must therefore be the result of enhanced GHG concentrations requires the assumptions about the smallness/magnitude of that natural variations, are insignificant.

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This is especially true for precipitation events. The hydrological literature has long noted the phenomenon of *Long-Term Persistence* (LTP) in rainfall data (Hurst 1951, Cohn and Lins 2005, Markonis and Koutsoyiannis 2015). LTP has a formal mathematical definition but it can be thought of intuitively as the presence of natural variations with strong autocorrelation properties that result in cycle-like behavior on long time scales. The presence of LTP requires very long data samples/records to obtain accurately accurate estimates of variance/variability. Analysis of, analysis of data samples that are records short relative to the LTP scale will tend to yield underestimate variability, therefore underestimated variances which in turn yields overstating the significance of apparent trends and underestimation underestimating of the likelihood of extreme events (Cohn and Lins 2005).

<sup>1</sup> For example, under the simplest statistical assumptions there is a 37 percent chance that a 100-year event is NOT present in a century-long record.

A good example of LTP is the eight-century long record of the annual minimum height of the Nile River observed at Roda Island in Cairo (shown below) in Figure B7.1.1. Since human influences on the global climate were negligible before the 20<sup>th</sup> century, the century-scale variability of the thirty-year average is entirely natural; Egyptians of the seventh and eight centuries would have been incorrect to assume that the worsening drought during that time was the “new normal.”

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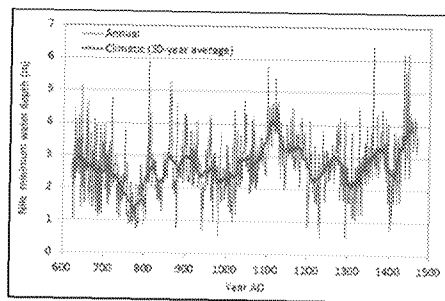


Figure B7.1.1: Nile River discharge [details, source]

With these caveats in mind, we examine the evidence for changes in selected weather and climate extremes. A theme that emerges when reviewing this topic is the wide gap between public perceptions and scientific evidence. It has become routine in media discussions, government and private sector discussions and even in some academic literature to make generalized assertions that extreme weather of all types is getting worse due to GHGs and climate change. Yet expert assessments have not typically drawn such sweeping conclusions and instead have emphasized the difficulty both of identifying specific trends and establishing a causal connection with anthropogenic forcing.

In the sections to follow we cite provide excerpts from various IPCC and NCA assessment reports denoting the sources as follows:

For the benefit of readers who may not have read the relevant reports in the Appendix to this chapter we will begin provide with extended excerpts of these findings from previous IPCC and NCA assessments, then in the remainder of this chapter survey additional data relevant to US and global extreme weather trends.

## 8.2 Review of IPCC and NCA Findings on Extreme Weather

The sources we review will be denoted as follows:

SREX: The IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (2012)

AR5: The IPCC Fifth Assessment Report Working Group 1 (2013)

AR6: The IPCC Sixth Assessment Report Working Group 1 (2021)

NCA17: The US Climate Science Special Report of the Fourth National Climate Assessment (2017) Volume I Chapter 6.



Note that in the excerpts, provided *italics* are in the original whereas boldface emphasis is added.

### 8.2.1 Overview Context: IPCC Assessment of signal emergence in extreme weather types (AR6 WG1 Table 12.12)

This chapter is concerned with detection of trends. Chapter 7 looked at attribution including for extreme weather. Since there is considerable public interest in the question of whether humans are causing trends in extreme weather to get worse it is useful to begin with the summary Table 8.2.1 which reproduces the findings of AR6 Table 12.12 which indicates, for 24 major weather event and impact types, whether a signal of anthropogenic forcing has been detected in the historical record (column 1), whether such a signal is likely to emerge by 2050 under the extreme RCP8.5 scenario (column 2) and whether it is likely to emerge by 2100 under RCP8.5 forcing (column 3). It should be borne in mind that the latter two columns suffer from the deficiencies of GCMs discussed in Chapter XX. And as we discussed in Ch. X7 on attribution, AR6 offers conflicting messages about attribution of extreme weather. Nevertheless, we provide this Table for reference context:

Several patterns stand out. First, detection of an anthropogenic signal is asserted with *high confidence* in only four of the 24 weather impact categories, and with *medium confidence* in a further four. The IPCC does NOT claim to have detected an anthropogenic signal in the remaining 16 categories. Of the four *high confidence* assertions, two are for changes in average temperatures (air and ocean), which are not measures of extreme weather. Further, two of the four *medium confidence* assertions are related to ocean chemistry and are also not related to extreme weather. The IPCC does NOT assert a detectable human influence on many non-temperature weather features such as wind, precipitation, flooding, and droughts.

Second, columns 2 and 3 show that the IPCC expects very few anthropogenic trends to emerge within this century, even under the most extreme forcing scenario. As we discuss in Section 1.2 the RCP8.5 scenario is an implausible high-end storyline, not a "base case" or "business-as-usual" projection. Even so, most weather impacts are not expected to show an anthropogenic signal this century. Natural variability dominates patterns of extreme weather systems and simplistic assertions of trend detection are frequently undermined by regional heterogeneity and trend reversals over time.

| Climate Impact Driver Type | Climate Impact Driver Category      | Already Evident in the Historical Record? | Emerging by 2050 in Most Extreme CO <sub>2</sub> Emissions Scenario? | Emerging by 2100 in Most Extreme CO <sub>2</sub> Emissions Scenario? |
|----------------------------|-------------------------------------|-------------------------------------------|----------------------------------------------------------------------|----------------------------------------------------------------------|
| Heat & Cold                | Average air temperature             | YES in most regions                       | YES                                                                  | YES                                                                  |
|                            | More heat extremes                  | YES in most regions                       | YES in most regions                                                  | YES                                                                  |
|                            | Fewer cold extremes                 | YES in a few regions                      | YES in most regions                                                  | YES                                                                  |
|                            | Less frost                          | NO                                        | NO                                                                   | NO                                                                   |
| Wat & Dry                  | Average Rain (Increase or Decrease) | NO                                        | YES (in up) YES (decr)                                               | YES (in up) YES (decr)                                               |
|                            | River Flooding                      | NO                                        | NO                                                                   | NO                                                                   |
|                            | Heavy precip & elevated flood       | NO                                        | NO                                                                   | YES in a few regions                                                 |
|                            | Landslide                           | NO                                        | NO                                                                   | NO                                                                   |
|                            | Aridity                             | NO                                        | NO                                                                   | NO                                                                   |
|                            | Hydrologic Drought                  | NO                                        | NO                                                                   | NO                                                                   |
|                            | Agricultural & ecological drought   | NO                                        | NO                                                                   | NO                                                                   |
|                            | Fire weather                        | NO                                        | NO                                                                   | NO                                                                   |
| Wind                       | Average wind speed                  | NO                                        | NO                                                                   | NO                                                                   |

|              |                                  |                          |                      |                 |
|--------------|----------------------------------|--------------------------|----------------------|-----------------|
|              | Severe wind storms               | NO                       | NO                   | NO              |
|              | Tropical cyclones                | NO                       | NO                   | NO              |
|              | Sand and dust storms             | NO                       | NO                   | NO              |
| Snow and ice | Snow, glacier & ice sheet        | NO                       | YES in a few regions | YES Arctic snow |
|              | Permafrost                       | YES                      | YES                  | YES             |
|              | Lake & river ice                 | NO                       | YES                  | YES             |
|              | Arctic sea ice                   | YES                      | YES                  | YES             |
|              | Antarctic sea ice                | NO                       | YES                  | YES             |
|              | Higher snowfall and ice storm    | NO                       | NO                   | NO              |
|              | Hail                             | NO                       | NO                   | NO              |
|              | Snow melt/retreat                | NO                       | NO                   | NO              |
|              | Perpetual snowfield              | NO                       | YES                  | YES             |
| Coastal      | Coastal flood                    | NO                       | NO                   | NO              |
|              | Coastal erosion                  | NO                       | NO                   | NO              |
|              | Average ocean temperature        | YES                      | YES                  | YES             |
| Open Ocean   | Major heat wave                  | NO                       | NO                   | NO              |
|              | Ocean acidity                    | NO                       | YES                  | YES             |
|              | Ocean salinity                   | YES                      | YES                  | YES             |
|              | Dissolved oxygen                 | YES (Pacific & S. Ocean) | YES                  | YES             |
| Other        | Air pollution/smog               | NO                       | NO                   | NO              |
|              | Solar or IR radiation at surface | NO                       | NO                   | NO              |

Table 8.2.1: IPCC AR6 summary of the probable emergence of an anthropogenic signal above natural climate variability for all global or regional “climate impact drivers” (CIDs) of concern for humans and ecosystems in response to increasing atmospheric greenhouse gas concentrations (primarily CO<sub>2</sub>). Source: Table adapted from report of Working Group I, Table 12.12. Red = high confidence; yellow = medium confidence; green = no anthropogenic signal detectable above natural variability (50% confidence).

Taking wind as an example, the IPCC claims that an anthropogenic signal has NOT yet emerged in average wind speeds, severe wind storms, tropical cyclones, or sand and dust storms, and none are expected to emerge this century even under an extreme emissions scenario. The same applies to drought and fire weather. This table alone suffices to illustrate the gap between IPCC expert assessments of extreme weather and discussions in the popular media and political arenas. As we show below, the Table reflects longstanding conclusions of the IPCC and other assessment bodies. In the next few sections we will simply present without comment excerpts from past assessment reports.<sup>2</sup> In selecting these excerpts, we’ve focused on the highest-level summaries to avoid accusations of bias through “cherry-picking.”

## B7.2 Context: detection is not attribution

This chapter is concerned with detection of trends. Chapter 29 looked at causal attribution, with Section 29.4 specifically addressing extreme weather. If no trend is detected, then clearly there is no basis for attribution. But even where a trend is observed attribution should not be assumed automatically to follow. Since there is considerable public interest in the question of whether humans are causing trends in extreme weather to get worse, it is useful to recall that AR6 Table 12.12 indicates that, for 34 major weather event and impact types, detection of an anthropogenic signal is

<sup>2</sup>In these excerpts we have added bold face emphasis while italicized emphasis on confidence terms appears in the original sources. Citations in quoted text can be found in the underlying reports but are not reproduced here.

asserted with *high confidence* in only four of the 34 weather impact categories, - and with *medium confidence* in a further four. The IPCC does not claim to have detected an anthropogenic signal in the remaining 26 categories. Of the four *high confidence* assertions, two are for changes in average temperatures (air and ocean), which are not measures of extreme weather. Also, two of the four *medium confidence* assertions are related to ocean chemistry and are also not related to extreme weather. The IPCC does not assert a detectable human influence on many non-temperature weather features such as wind, precipitation, flooding, and drought.

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### 87.2.73 Hurricanes and Tropical Cyclones

The AR6 assessment provides the following assessment of tropical cyclones (TCs; used here to be synonymous with hurricanes):

AR6: There is *low confidence* in most reported long-term (multidecadal to centennial) trends in TC frequency or intensity-based metrics due to changes in the technology used to collect the best-track data. (IPCC, 2021)

AR6: It is *likely* that the global proportion of major (Category 3–5) tropical cyclone occurrence has increased over the last four decades. . . . There is *low confidence* in long-term (multi-decadal to centennial) trends in the frequency of all-category tropical cyclones. (IPCC, 2021)

AR6: A subset of the best-track data corresponding to hurricanes that have directly impacted the United States since 1900 is considered to be reliable, and shows *no trend* in the frequency of U.S. landfall events. (IPCC, 2021)

Since 1980, when satellite observations fully covered the global oceans, we have confidence in the numbers of total global hurricanes and major hurricanes (Category 3 and higher). Figure 87.3.1 shows that on average, each year there are about 50 hurricanes, with about 25 reaching major hurricane status (RN Maue, 2025). Substantial year-to-year and decadal variability is seen; over the time period, there is a slight decreasing trend in the number of hurricanes and a slight but insignificant increasing trend in the number of major hurricanes. From these two trends, it is inferred that there is an overall trend of increasing percentage of major hurricanes, relative to the total number of hurricanes.

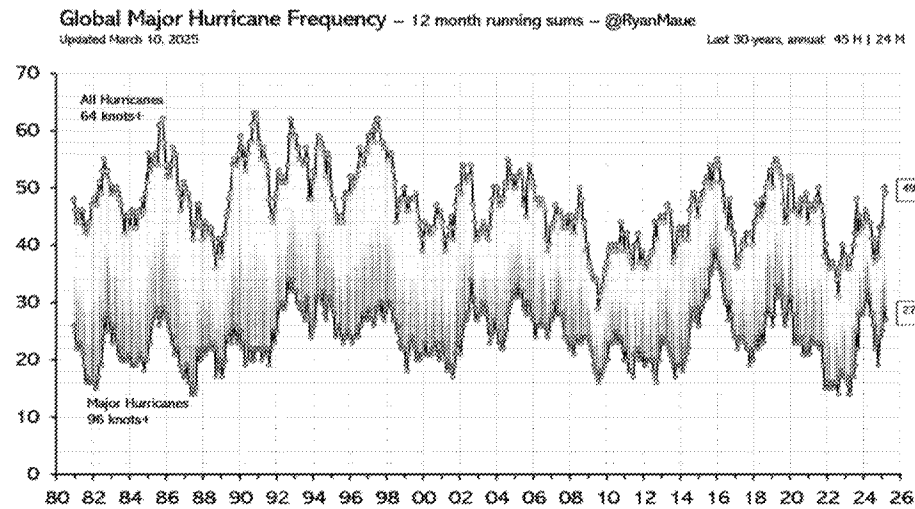


Figure 87.3.1: Global frequency of hurricanes and major hurricanes since 1980.

Global hurricane statistics are dominated by the Northwest Pacific Ocean which accounts for ~35 percent of total global hurricanes whereas the Atlantic accounts for ~15% percent of global

hurricanes (CSU, 2025). Data in the Atlantic Ocean extends further back than in the other ocean basins, and is most relevant to U.S. policy makers.

Figure 7.3.2 shows the frequency of Atlantic hurricanes (HR) and major hurricanes (MHR, Category 3 and higher) back to 1920. Data prior to 1965 (the onset of satellite observations in the Atlantic, shaded in blue) shows some undercounting, with data prior to 1920 showing substantial undercounting (GA Vecchi and TR Knutson, 2011). All measures of Atlantic hurricane activity show a significant increase since 1970. However, the period from 1971-1994 was a period of exceptionally low activity, with high values of hurricane activity (comparable to the past two decades, even with undercounting) also observed during the 1950's and 1960's, and also even in the 1930's.

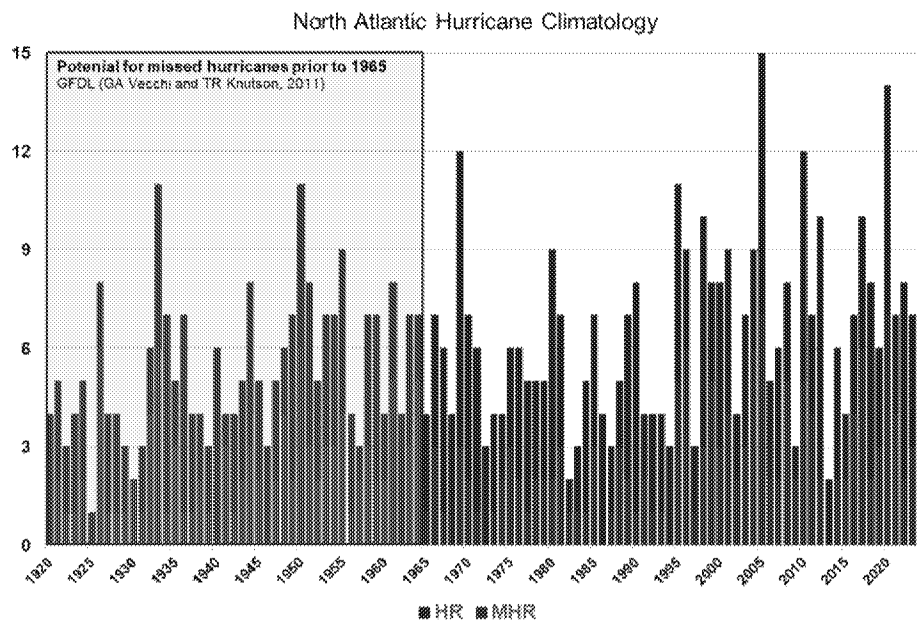


Figure 7.3.2: Atlantic frequency of hurricanes and major hurricanes since 1920. Source (NHC, 2024)

It is seen from Figure 7.3.2 that Atlantic hurricanes show strong variations on decadal and multi-decadal time scales in the observed record. These variations are associated primarily with the Atlantic Multidecadal Oscillation (AMO), which is associated with basin-wide sea surface temperature and sea level pressure fluctuations associated with large scale ocean circulation patterns. The AMO was in its warm phase during 1926-1970 and 1995-present; the AMO was in its cool phase during 1971-1994. The greatest impact of the AMO is on the number of major hurricanes (Category 3+). The relationship of the AMO to major hurricane activity in the Atlantic was identified by Goldenberger et al. (2001) to be associated with above normal SSTs and decreased vertical shear associated with the warm AMO (see also GD-Bell and M-Chelliah, 2006; PI-Klotzbach et al., 2018).

Klotzbach et al. (2018) conducted a comprehensive evaluation of the landfalling hurricane data for the Continental U.S. since 1900. Figure 8.7.3.3 updates the Klotzbach et al. analysis through 2024. While the largest numbers of hurricanes are from 2004, 2005 and 2020, the overall trend since 1920 is not statistically significant from zero. Figure 8.7.3.3 also shows the time series for major hurricane landfalls (Category 3-5). The largest year in the record is 2005, with 4 major hurricane landfalls. However, during the period 2006 through 2016, there were no major hurricanes striking the U.S., which is the longest such period in the record since 1920.

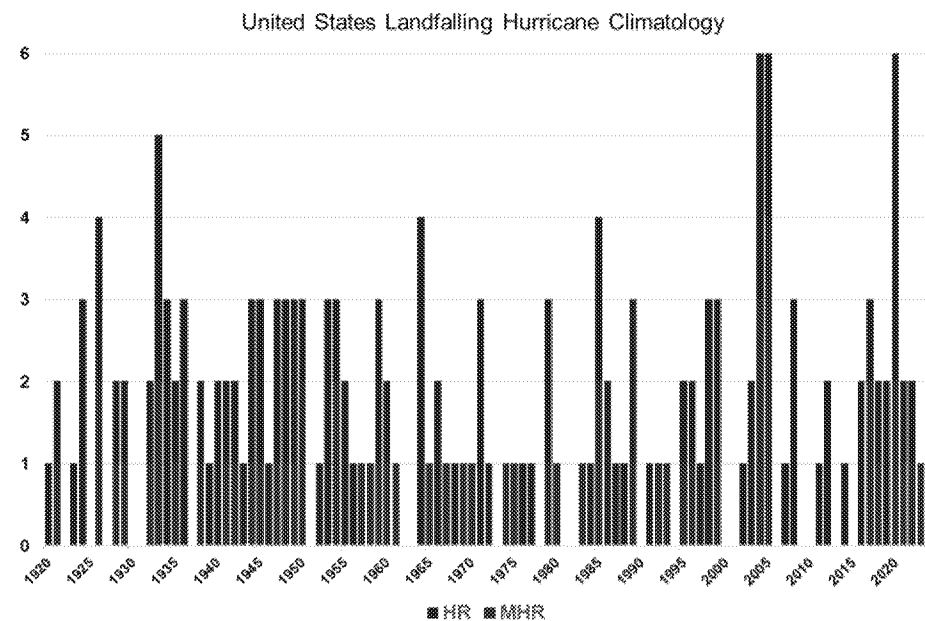


Figure 8.7.3.3: US landfalling frequency of hurricanes and major hurricanes since 1920. Source (NOAA HRD(a), 2024)

Substantial interannual to multidecadal variability in U.S. landfall activity is seen Figure 7.3.3. In Klotzbach et al. (2018) examined how the landfall counts vary with ENSO (El Niño versus La Niña) and the warm versus cold phases of the Atlantic Multidecadal Oscillation (AMO).

Villarini et al. (2012) provide an analysis of U.S. hurricane landfalls back to 1878. While it is possible that some landfalls were missed in the late 19<sup>th</sup> century owing to sparsely populated regions on the Gulf Coast, it is remarkable that the highest year in the entire record, with 7 landfalls, is 1886.

Table 8.7.3.1 shows the 10 strongest hurricanes (plus ties) to make U.S. landfall. Of the hurricanes that have made landfall with sustained winds greater than 150 mph, only one has occurred in the busy period since 2004 the 21<sup>st</sup> century.

**Table 8.7.3.1** Strongest hurricanes to make landfall along the US coast. Source (NOAA HRD(b), 2024)

| Rank | Year | Landfall Wind (MPH) | Name          |
|------|------|---------------------|---------------|
| 1    | 1935 | 185                 | "Labor Day"   |
| 2    | 1969 | 175                 | Camille       |
| 3    | 1992 | 165                 | Andrew        |
| 4    | 2018 | 160                 | Michael       |
| 5    | 1856 | 150                 | "Last Island" |
| 5    | 1886 | 150                 | "Indianola"   |
| 5    | 1919 | 150                 | -----         |
| 5    | 1932 | 150                 | "Freeport"    |
| 5    | 2004 | 150                 | Charley       |
| 5    | 2020 | 150                 | Laura         |
| 5    | 2021 | 150                 | Ida           |
| 5    | 2022 | 150                 | Ian           |

While an increase in hurricane intensity has long been hypothesized to occur as global sea surface temperatures increase, identification of any significant trend in the hurricane data is hampered by a short data record and substantial natural variability.

In summary, analyses of both global and regional variability and trends of hurricane activity provide the basis for detecting changes and understanding their causes. The relatively short historical record of hurricane activity, and the even shorter record from the satellite era, is not sufficient to assess whether recent hurricane activity is unusual relative to the background natural variability. Atlantic hurricane processes are influenced substantially by the natural modes of ocean circulation variability in the Atlantic, notably the Atlantic Multidecadal Oscillation. The AR6 assessed this topic as follows:

AR6: There is low confidence in most reported long-term (multidecadal to centennial) trends in TC frequency or intensity-based metrics due to changes in the technology used to collect the best-track data. (Chapter 1.1, p. 1585)

AR6: It is likely that the global proportion of major (Category 3–5) tropical cyclone occurrence has increased over the last four decades. There is low confidence in long-term (multi-decadal to centennial) trends in the frequency of all-category tropical cyclones. (SPM A.3.4)

AR6: A subset of the best-track data corresponding to hurricanes that have directly impacted the United States since 1900 is considered to be reliable, and shows no trend in the frequency of U.S. landfall events. (Chapter 1.1 Summary, p. 1585)

Hurricane strength records for the North Atlantic and the Western Pacific go back to 1950 and the record does not show an increase in either total or major TCs. Figure 8.3.1 was published by Roger Pielke Jr. as an update to the Best Track data series originally presented in Weinkle et al. (2012).

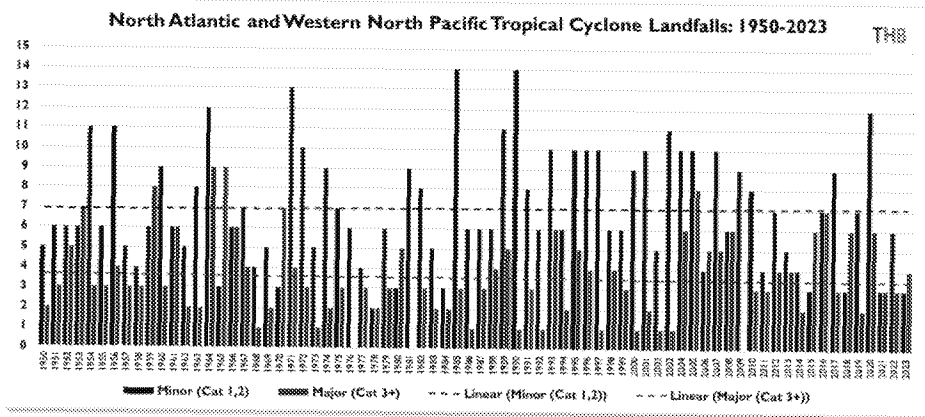


Figure 8.3.1: Tropical Cyclone Landfalls. Source: [HYPERLINK "https://rogerpielkejr.substack.com/p/global-tropical-cyclones"], Weinkle et al. (2012)

Similarly, Figure 8.3.2 (Maue 2025, [HYPERLINK "https://climatlas.com/tropical/"]) shows that both all hurricanes and major hurricanes have not become more common since 1980, the period of rapidly growing human influences. In fact, both numbers have trended down slightly since the 1990s.

Commented [A2]: Cite the Climate Atlas of Dr. Ryan Maue

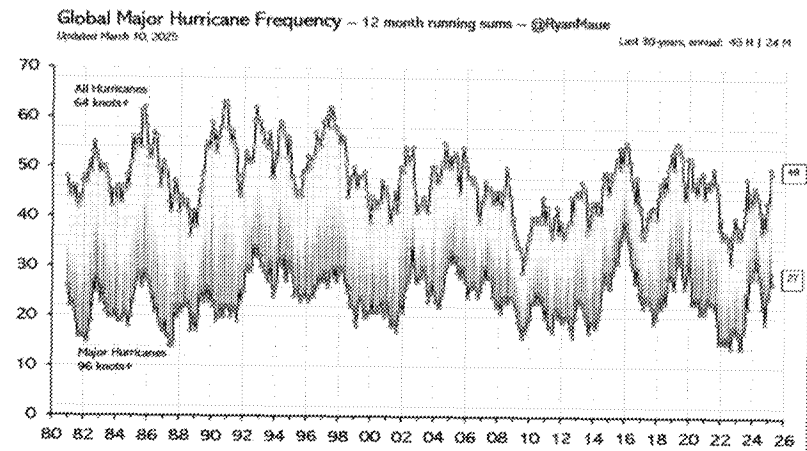


Figure 8.3.2: Global hurricane frequency. Source: Maue (2025)

A metric that combines the number, duration, and strength of TCs is the Accumulated Cyclone Energy (ACE) index maintained at Colorado State University, shown in Figure 8.3.3. It clearly shows no long-term increase, in fact declining slightly since 1990.



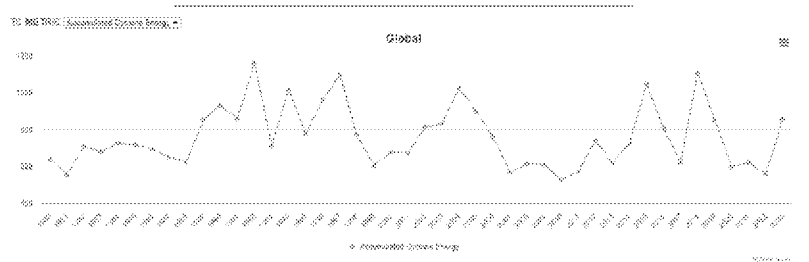


Figure 8.3.3: Global Accumulated Cyclone Energy. Source: Klotzbach (2025)

[HYPERLINK "<https://tropical.atmos.colostate.edu/Realtime/index.php?arch&loc=global>"]

Note that Tu et al. (2024) report that the Power Dissipation Index (PDI), another different measure that combines hurricane number, duration, and strength, has either remained unchanged or has declined in all global oceanic basins since the mid-1990s.

Today's global climate simulations are too coarse to project changes in TCs directly. Rather, projections are derived from finer "downscaled" simulations or proxies involving sea surface temperatures, winds, and aerosols. By those methods, a warming climate is expected to show declining hurricane formation rates (Chang et al. 2022). Climate models also project fewer Tropical Cyclones under future global warming, and even though models project they will increase in strength, the annual averages of rainfall maxima decline (Stancfield et al. 2020).

#### 8.3 Tornadoes SREX (p. 159):

There have been no significant trends observed in global tropical cyclone frequency records, including over the present 40-year period of satellite observations (e.g. Webster et al., 2005). Regional trends in tropical cyclone frequency have been identified in the North Atlantic, but the fidelity of these trends is debated (Holland and Webster, 2007; Landsea, 2007; Mann et al., 2007a). Different methods for estimating undercounts in the earlier part of the North Atlantic tropical cyclone record provide mixed conclusions (Chang and Guo, 2007; Mann et al., 2007b; Kunkel et al., 2008; Vecchi and Knutson, 2008). Regional trends have not been detected in other oceans (Chan and Xu, 2009; Kubota and Chan, 2009; Callaghan and Power, 2011). It thus remains uncertain whether any observed increases in tropical cyclone frequency on time scales longer than about 40 years are robust after accounting for past changes in observing capabilities (Knutson et al., 2010).

#### AR5 (pp. 216-17):

Current data sets indicate no significant observed trends in global tropical cyclone frequency over the past century and it remains uncertain whether any reported long-term increases in tropical cyclone frequency are robust, after accounting for past changes in observing capabilities (Knutson et al., 2010). No robust trends in annual numbers of tropical storms, hurricanes and major hurricanes counts have been identified over the past 100 years in the North Atlantic basin. Measures of land-falling tropical cyclone frequency

(Figure 2.34) are generally considered to be more reliable than counts of all storms which tend to be strongly influenced by those that are weak and/or short lived. Callaghan and Power (2011) find a statistically significant decrease in Eastern Australia land-falling tropical cyclones since the late 19th century although including 2010/2011 season data this trend becomes non-significant (i.e. a trend of zero lies just inside the 90% confidence interval). Significant trends are not found in other oceans on shorter time scales (Chan and Xu, 2009; Kubota and Chan, 2009; Mohapatra et al., 2011; Weinkle et al., 2012), although Grinstead et al. (2012) find a significant positive trend in eastern USA using tide gauge data from 1923–2008 as a proxy for storm surges associated with land-falling hurricanes. Differences between tropical cyclone studies highlight the challenges that still lie ahead in assessing long-term trends.

In summary, this assessment does not revise the SREX conclusion of *low confidence* that any reported long-term (centennial) increases in tropical cyclone activity are robust after accounting for past changes in observing capabilities. More recent assessments indicate that it is *unlikely* that annual numbers of tropical storms, hurricanes and major hurricanes counts have increased over the past 100 years in the North Atlantic basin. Evidence, however, is for a virtually certain increase in the frequency and intensity of the strongest tropical cyclones since the 1970s in that region.

AR6 (p. 1585)

There is *low confidence* in most reported long-term (multidecadal to centennial) trends in TC frequency or intensity-based metrics due to changes in the technology used to collect the best-track data. This should not be interpreted as implying that no physical (real) trends exist, but rather as indicating that either the quality or the temporal length of the data is not adequate to provide robust trend detection statements, particularly in the presence of multidecadal variability.

There are previous and ongoing efforts to homogenize the best-track data (Elner et al., 2009; Kossin et al., 2013, 2020; Choy et al., 2015; Landsea, 2015; Emanuel et al., 2018) and there is substantial literature that finds positive trends in intensity-related metrics in the best-track during the “satellite period”, which is generally limited to the past ~40 years (Kang and Elner, 2012; Kishitani et al., 2012; Kossin et al., 2013, 2020; Mei and Xie, 2016; Zhao et al., 2018; Tawale and Tsuboki, 2019). When best-track trends are tested using homogenized data, the intensity trends generally remain positive, but are smaller in amplitude (Kossin et al., 2013; Holland and Bruyère, 2014). Kossin et al. (2020) extended the homogenized TC intensity record to the period 1979–2017 and identified significant global increases in major TC exceedance probability of about 6% per decade.<sup>2</sup> In addition to trends in TC intensity, there is evidence that TC intensification rates and the

<sup>2</sup>The underlined text referenced a study (Kossin et al., 2020) that later retracted a portion of its findings. Those authors assembled a dataset on global TC intensity spanning 1979 to 2017 from which they claimed that the global fraction of TCs reaching major status (Cat 3–5) rose from 27% during 1979–1997 to 31% during 1998–2017 and that the increase was statistically significant. However, closer examination of their results showed a significant increase only in the North Atlantic (15% to 24%) whereas changes in all other basins (Eastern Pacific, Western Pacific, North Indian, South Indian, South Pacific) were not statistically significant in a subsequent correction ([HYPERLINK "<https://www.pnas.org/doi/10.1073/pnas.2021573117>"]]). Kossin et al. stated that the global probability of observing a major TC rose from 24% during 1979–1997 to 27% in the same period and that the evidence for statistical significance was now weaker. Nevertheless, the authors claimed that the correction did not affect their conclusions.

frequency of rapid intensification events have increased within the satellite era (Gschsttawel et al., 2012; Balaguru et al., 2018; Bhatia et al., 2018). The increase in intensification rates is found in the best-track as well as the homogenized intensity data.

**A subset of the best-track data corresponding to hurricanes that have directly impacted the United States since 1900 is considered to be reliable, and shows no trend in the frequency of U.S. landfall events (Knutson et al., 2019).**

AR6: [O]bservational trends in tornadoes, hail, and lightning associated with severe convective storms are not robustly detected due to insufficient coverage of the long-term observations. There is medium confidence that the mean annual number of tornadoes in the USA has remained relatively constant. (Chapter 11, section 11.7.3, p. 1594)

As noted there is no evidence of trend in US tornadoes or extreme convective storms. Extreme precipitation will be discussed further below.

#### 8.7.34 Temperature extremes

The AR6 assessment focused on the period after 1950 and reported increasing trends in heatwave frequency and intensity. The NCA17 however noted that heatwave activity in the US reached a peak in the 1930s.

AR6: "It is *virtually certain* that hot extremes (including heatwaves) have become more frequent and more intense across most land regions since the 1950s, while cold extremes (including cold waves) have become less frequent and less severe" (SPM, A3.1)

AR6: "In North America, there is very robust evidence for a *very likely* increase in the intensity and frequency of hot extremes and decrease in the intensity and frequency of cold extremes for the whole continent, though there are substantial spatial and seasonal variations in the trends. Minimum temperatures display warming consistently across the continent, while there are more contrasting trends in the annual maximum daily temperatures in parts of the USA." (Chapter 11, p. 1556)

NCA17: "Changes in warm extremes are more nuanced than changes in cold extremes. For instance, the warmest daily temperature of the year increased in some parts of the West over the past century, but there were decreases in almost all locations east of the Rocky Mountains. In fact, all eastern regions experienced a net decrease, most notably the Midwest (about 2.2°F [1.2°C]) and the Southeast (roughly 1.5°F [0.8°C])." (pp. 190-191)

NCA17: "Since the mid-1960s, there has been only a very slight increase in the warmest daily temperature of the year (amidst large interannual variability). Heat waves (6-day periods with a maximum temperature above the 90th percentile for 1961–1990) increased in frequency until the mid-1930s, became considerably less common through the mid-1960s, and increased in frequency again thereafter. As with warm daily temperatures, heat wave magnitude reached a maximum in the 1930s." (pp. 190-191)

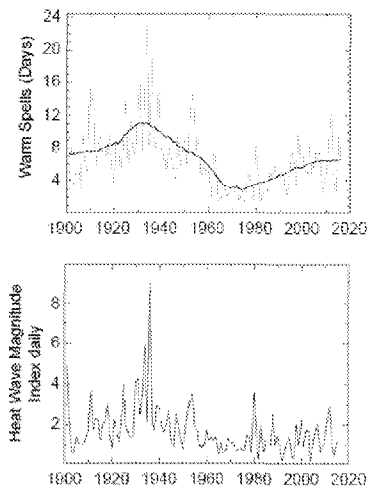


Figure 8.7.34.1: US Heat waves since 1900. Source: NCA17 Figure 6.4

#### 8.7.34.1 Temperatures in the US are becoming less extreme

Daily maximum temperatures in the warm season (TMax, May-Sep) and daily minimum temperatures in the cold season (TMin, Dec-Mar) are available beginning in Dec. 1898 (126 years). The dataset consists of 1,211 CONUS stations designated as United States Historical Climate Network or USHCN stations (see Figure 8.7.34.12; Quinlan et al. 1997, Karl et al. 1999). These stations were selected by NOAA as having the fewest problematic issues with gaps, station moves and instrument changes. Where gaps still exist, nearby stations (bias-corrected) were merged so that the median volume of data available for a station is 98%. Although there are certainly errors in the dataset, with over 1,000 stations we can have relatively high confidence in any underlying signal that might be discovered.

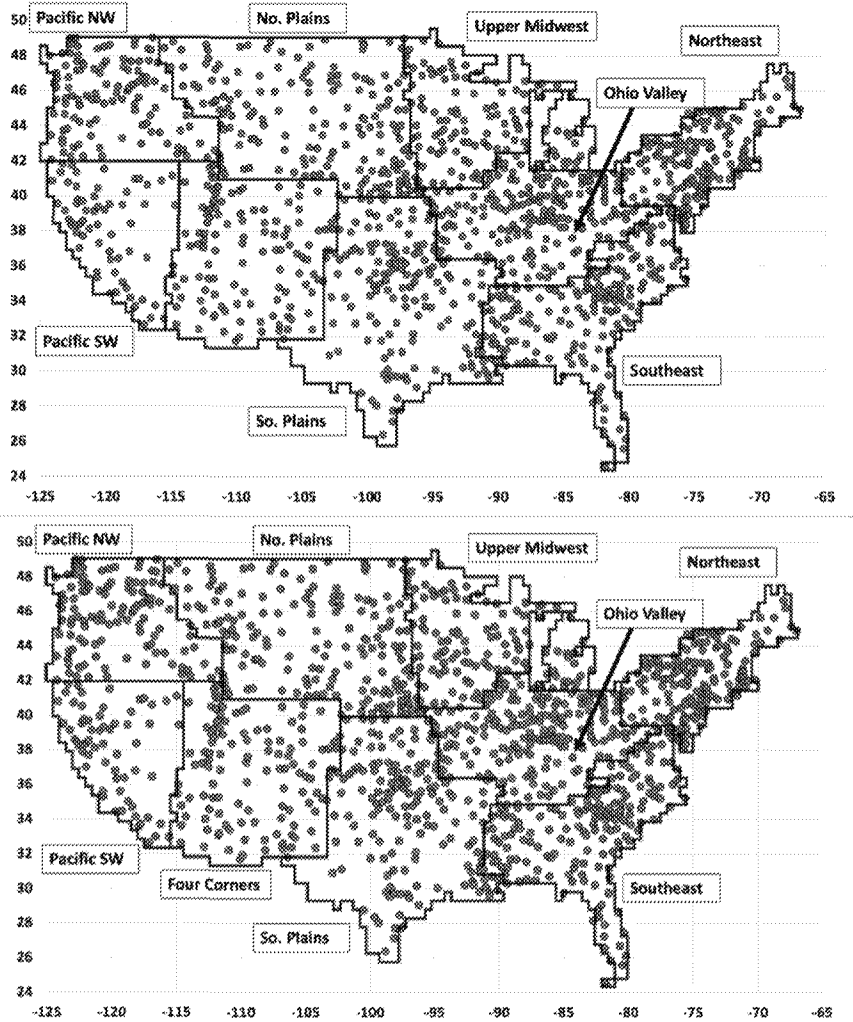


Figure 8.7.34.42 Locations of USHCN temperature stations. Source: USHCN.

We begin with the question of whether the occurrence of daily record high or low temperatures changed has changed since Dec 1898. Each warm-season has 153 days (1 May to 30 Sep) and each cold-season has 122 days (1 Dec to 31 Mar). For each station and day, we calculated the year in which the record highest (lowest) temperature occurred. With 126 years of observations, if there were no temperature trends over time, the expected number of records for TMax would be 1.21 ( $=153/126$ ) per station per year and for TMin 0.96 ( $=122/126$ ) per station per year. Figure 8.7.4-34.3 indicates the observed distribution in time of the occurrence of these extreme events.

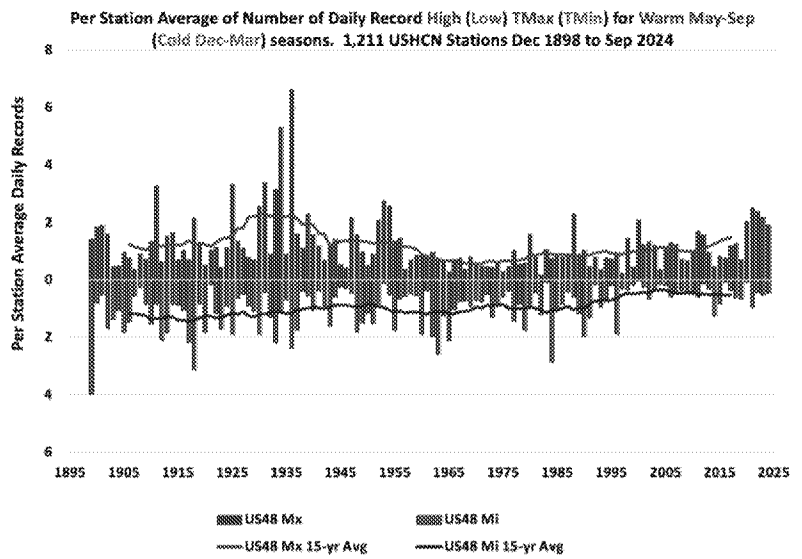


Figure 8-7.34.23 Number of daily record High (red) and Low (blue) for warm and cold seasons in the CONUS. The lines represent the 15-year running, centered average. Source: 1,211 USHCN stations supplemented as needed to achieve a minimum of 92% of observations in the 126-year period since Dec. 1898.

The results indicate a common feature in many metrics of warm-season extremes in the CONUS - the exceptional heat of the 1920s and especially the 1930s, peaking in 1936. On a per-station average, 60% of the TMax records and 59% of the TMin records occurred in the first half of the period (1899-1961).

On the cold side, the Valentine's Day Arctic outbreak in Feb. 1899 stands as the most extensive cold extreme experienced by the CONUS, with 1917 in 2nd place. The frequency of cold records has declined, especially over the last quarter of the period in which only 13% of the extreme cold events were measured. In contrast, 25% of the extreme TMax records were achieved in the last quarter, in accordance with statistical expectations. These general features have been noted in past assessments (see above, IPCC AR5, IPCC AR6, NCA4, NCA5 [7]). Combining the two records the overall reduction in numbers of both cold and hot extremes over the past century indicates a climate less prone to extremes.

This pattern is also shown in Figure 8-7.34.43. For each station and for each year the hottest warm season and coldest cold-season temperatures were calculated and converted to anomalies relative to the station's long-term warm and cold season (respectively) averages. Then the differences between these were computed by station and geographically-averaged over all stations, thus yielding an

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annual measure of the expected range of local extreme temperatures for each year. Figure 8-7.4.4.11 shows the 15-year trailing average of this measure, which has clearly declined over the past century.

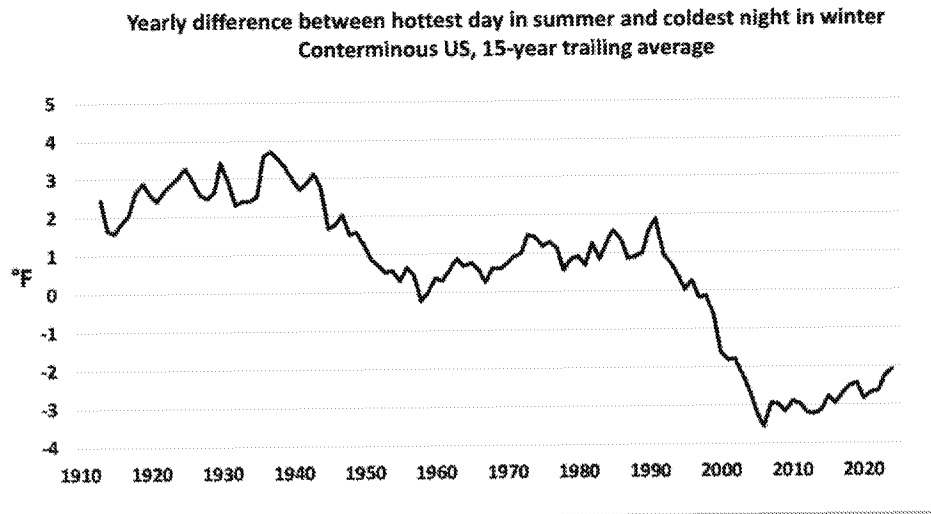


Figure 8-7.4.4.11. 15-year trailing average of the difference each year of each station's hottest warm-season TMax and coldest cold-season TMin relative to the long-term average. Source: USHCN, author calculations.

The average difference for each station between the hottest summer TMax and coldest winter TMin has declined by about 5°F in the past 126 years. The decline is due mostly to warmer winter TMin, but a decline in the magnitude of summer TMax is also a factor. The rise in TMin has been strongly related to the growing presence of manufactured surfaces around the weather stations over the last 100+ years (the so-called urban heat island effect; Spencer et al. 2025).

Summarizing Figures 8-7.4.134.23 and 8-7.4.2.3-3.4.4, in summary, while temperature extremes are regularly experienced in the US and attract a great deal of media attention, long-term records show the US climate has become less extreme over time (milder) when measured in terms of the range between warm season maxima and cold season minima.

#### 8.7.4.4.2 Exceedances of a heat threshold

Under the heading of "The Risk of Temperature Extremes is Changing", the most recent US National Climate Assessment report (NCA235) notes the increase in a threshold metric of number of days at or above 95°F, stating,

"The western US has been particularly affected by extreme heat since the 1980s ... experiencing a larger increase in days over 95°F, as would be expected given the greater warming in that region relative to the eastern US. Several major heatwaves have affected the US since 2018, including a record-shattering event in the Pacific Northwest in 2021."

Are the occurrences of 95°F days changing? In a climate as varied as that of CONUS, threshold statistics can be misleading. A region with many stations that have near 95°F TMax average temperatures in the summer might see large swings in the metric when only small changes in average temperature occur. Elsewhere with stations that either rarely or virtually always achieve 95°F TMax temperatures, a small change will not impact the results much at all. In the past 126 years, the average CONUS station experienced 129 days exceeding 95°F per 6-yr period, but the regional values range from 278 in the Southern Plains to 9 in the Northeast. Thus, one needs to view such threshold analyses with caution.

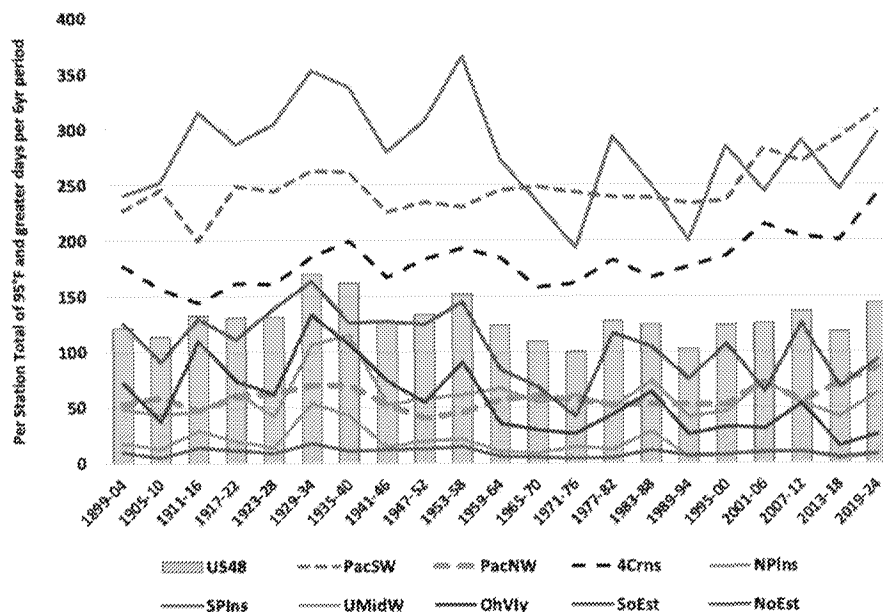


Figure 8.7.4.334.45. Total number of days  $\geq 95^{\circ}\text{F}$  in 6-yr periods. US 48 (bars) and regions (lines). Interval is 6-years as this is divisible into 126. Source: USHCN, author calculations.

In Fig. 8.7.4.334.45 we see that only three of the nine regions, all in the West, have experienced upward trends in the number of 95°F or hotter days (dashed lines). The CONUS, as a whole has not, and the other six regions have experienced declines.



The Pacific NW heatwave of 2021 is referenced as often the NCA523-claim an event we examine more closely in Section 69.4. The evidence indicates that it was a “black swan” event, i.e., a single, unprecedented event in the record, not part of a pattern of increasing extreme heat. For example, the 5-day average tropospheric grid-point temperature anomaly over the Pacific NW during that event was +10.8 C, the most extreme NH Northern Hemisphere grid point summer anomaly in the 46 years from over 4 million grid values. In contrast, the global temperature anomaly during that time was virtually zero (+0.03 C, Mass et al. 2024).

The heading “The Risk of Temperature Extremes is Changing” WHERE IS THIS HEADING FROM suggests positive trends are now being observed in threshold temperatures on a widespread basis, but that is not evidenced in the combined CONUS results of the figures above.

#### 8-7.4.34.3 Heatwaves

Heatwaves (consecutive days that exceed an extreme threshold) have a greater societal impact than a single daily record temperature. We measure “Heatwave Days” here as the count of all days in May-Sep each year that exceed the 90<sup>th</sup> percentile and that lie within a run period of at least six consecutive days. This is equivalent to the method used in NCA517, except that the reference period here is the entire record 1899-2024, while NCA517 truncated the reference period to 1961-1990, a cool period. That truncation boosts positive results (days exceeding the 90<sup>th</sup> percentile) in periods warmer than the reference period, especially starting in 1960 and moving to the present (see *Urban Influences* below).

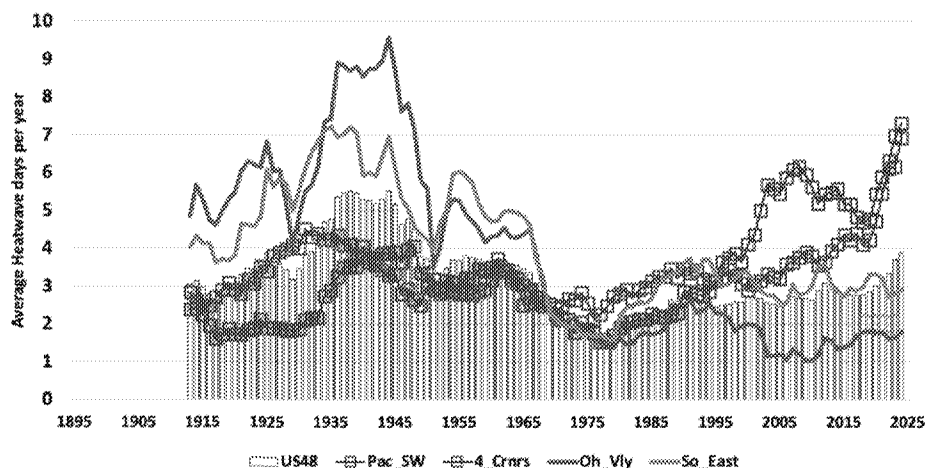


Figure 8-7.4.34.56 15-year trailing average of number of heatwave days per year per station in the CONUS (bars) and four regions: Pac\_SW (purple squares, CA, NV), 4\_Cntrs (red squares, AZ,NM,UT,CO), Oh\_Vly (blue, MO, IL, KY, TN, IN, OH, WV) and So\_East (green, MS, AL, GA, FL, SC, NC, VA).

Figure 8.7.4-124.56 indicates again the excessive heat of the first half of the 20<sup>th</sup> century, primarily in the eastern two-thirds of the nation, as seen in the regional values for the Ohio Valley and the Southeast as examples. The West has seen a recent increase of heatwave days and the two regions with the highest number are shown, the Pacific Southwest and the Four-Corners (NCA523). This indicates that the background warm season circulation favored heatwaves in the eastern portions of the country in the first half of the 20<sup>th</sup> century, but in the 21<sup>st</sup> century the patterns have favored heatwaves in the West. For CONUS as a whole, heatwaves are no more common today than they were a century ago.

Of interest here is the regional variation of this metric. The four northern regions (Pacific NW, Northern Plains, Upper Midwest and Northeast) on average experience 15 to 27 heatwave days per 15-year period. In contrast, the five southern regions (Pacific Southwest, 4-Corners, Southern Plains, Ohio Valley and Southeast) see 37 to 54 such days, essentially twice as many. This suggests the summer circulation pattern is more prone to stationary events in the southern regions while transient systems in the northern regions are more common and thus cut short these potentially longer events.

#### 8.7.3.4.4 Urban influences

The NCA523 directs readers to the website [HYPERLINK "<https://www.globalchange.gov/indicators/heat-waves>"]. (USGCRP 2023) to view the number of urban heatwaves by decade from the 1960s. The figure shows a monotonic increase in each decade from 2 occurrences per year in the 1960s to 6 in the 2020s. The definition of a heatwave is an unusual but practical measure of human discomfort - a period of at least 2 consecutive days when the minimum apparent temperature (combination of temperature and humidity) exceeds the 85<sup>th</sup> percentile. Note too, the dataset is limited to the 50 largest U.S. cities.

These increasing values since 1960 presented in USGCRP (2023) are entirely reasonable, but are unrelated to GHG emissions for at least two reasons. Urbanization in these cities is a major factor in the rise of TMin relative to co-located TMax and relative to TMin at rural stations. Also, the 1960s was the coldest decade and 1970s the second coldest decade since the 1910's, so this starting date preconditions the time series to show increases. This does not dismiss the real rise in nighttime temperatures in major U. S. cities and the societal impacts associated with these changes. However, we note for a variety of reasons, that summer TMax (especially in rural areas) serves as better response variable for detecting potential changes in heatwaves influenced by changes in the background climate due, for example, to increasing GHGs (Christy et al. 2009). For the CONUS as a whole, the evidence in this section suggests GHG emissions have had little-to-no effect on heatwaves.

#### 8.4 Tornadoes

AR6: [O]bservational trends in tornadoes, hail, and lightning associated with severe convective storms are not robustly detected due to inefficient coverage of the long-term observations. There is medium confidence that the mean annual number of tornadoes in the USA has remained relatively constant. (Chapter 11, section 11.7.3, p.1504)

As noted there is no evidence of trends in US tornado or extreme convective storms. Extreme precipitation will be discussed below.

#### 8.7.455 Extreme precipitation

The IPCC AR6 assessed that an increase in heavy precipitation has been observed in data starting in the 1950s.

AR6: "The frequency and intensity of heavy precipitation events have increased since the 1950s over most land area for which observational data are sufficient for trend analysis (high confidence)." (SPM.A3.2)

AR6: "In North America, there is robust evidence that the magnitude and intensity of extreme precipitation has *very likely* increased since the 1950s. Both [one-day maximal and 5-day maxima] have significantly increased in North America during 1950-2018" (Chapter 11, p. 1560)

However other data sources indicate less evidence of increasing extreme precipitation when examined over a longer time scale.

Figure 8.7.45.1 shows that US long term data from NOAA (1895-2023) shows an insignificantly increasing tendency toward extreme wetness (+0.0001% per year)

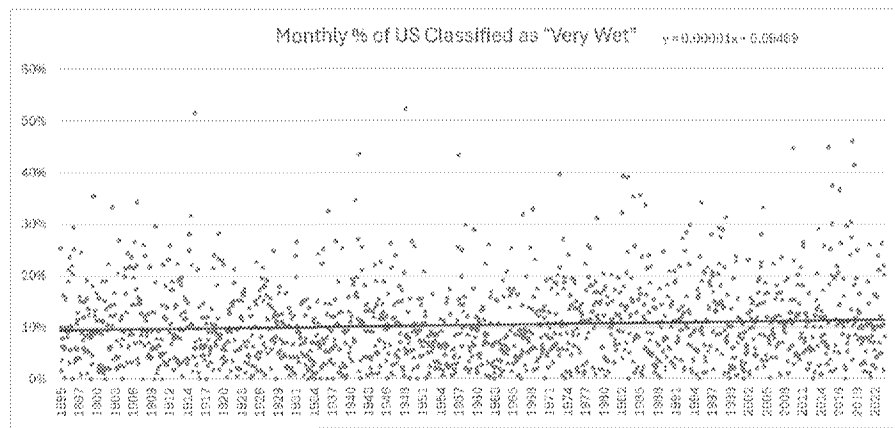


Figure 8.7.45.1: Long term US wetness (%). Source: NOAA [HYPERLINK "<https://www.ncei.noaa.gov/access/monitoring/uspa/wet-dry/0/>"]

Because precipitation involves a discrete phase change (water vapor to liquid), it is stochastic and episodic in character and requires careful statistical treatment to understand variability over long time periods (see 8.7.1 Introduction). The US National Climate Assessments (NCA417, NCA523) have highlighted an increase in the occurrence of the heaviest precipitation events (defined in different ways) primarily in the eastern half of the CONUS, especially the Northeast, when starting the analysis in either 1901 or 1958. Interestingly, the regional variations indicate that the largest increases in

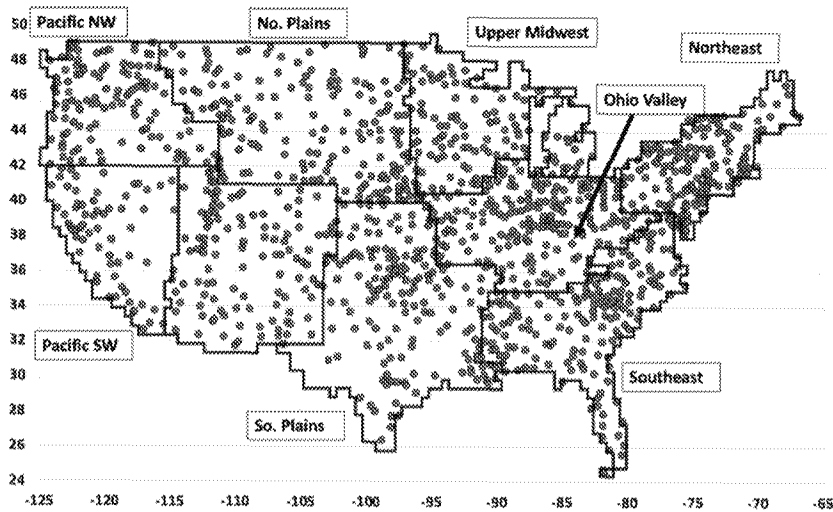
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extreme events are in the Northeast and the smallest in the West, a trend pattern counter to the changes in temperature extremes.



McKittrick and Christy (2019) examined long-term and consistent station observations of extreme daily precipitation to test some of these NCA claims for the Southeast and West Coast. When the time series were extended back in time (as far as 1872 in some cases) or when starting later (1978), there were no significant trends for either region.

For this report we updated these findings with similarly constructed observations from 29 stations on the CONUS Pacific Coast (1893ff from San Diego, CA to Blaine WA) and 24 stations in the humid Southeast (1872ff from Austin TX to Washington DC), and also adding 21 stations in the Northeast (1888ff from Buffalo, NY to Gardiner ME). The locations are shown in Figure 2.5.2. The results of applying the analysis of McKittrick and Christy (2019) were as follows for each region, then indicating the statistical updates followed by further explanations:



{will generate

map of stations - RM}

Figure 7.5.2: Locations of precipitation monitoring stations used in this report. Green: Pacific coast. Blue: Northeast. Red: Southeast.

#### Pacific region:

- The trend in average precipitation is significant (downwards) in Astoria, insignificant elsewhere.
- The trend in rainfall variance is positive and significant in Big Sur, insignificant elsewhere.
- The trend in daily maximum precipitation is positive and significant in Aberdeen and Big Sur and negative and significant in Newport (insignificant elsewhere).
- Averaged over all stations in the region none of these three trend parameters is statistically significant.

#### Southeast region:

- The trend in average precipitation is positive and significant in Mobile and Quitman, insignificant elsewhere.
- The trend in rainfall variance is positive and significant in Mobile, insignificant elsewhere.
- The trend in daily maximum precipitation is positive and significant in Vicksburg and Norfolk, insignificant elsewhere.
- Averaged over all stations in the region none of these three trend parameters is statistically significant.

#### Northeast region:

- The trend in average precipitation is positive and significant in 9 of 21 locations and in the region averaged overall.
- The trend in rainfall variance is positive and significant in Portland, Albany and Buffalo, insignificant elsewhere.
- The trend in daily maximum precipitation is positive and significant in Portland and Gardiner, insignificant elsewhere.
- Averaged over all stations in the region the trend parameters for variance and maximum precipitation are not statistically significant.

#### Pacific Coast heavy rainfall events

- \* Average precipitation trend is significant (downwards) in Astoria OR; insignificant elsewhere.
- \* The trend in rainfall variance is positive and significant in Big Sur CA; insignificant elsewhere.
- \* The trend in daily maximum precipitation is positive and significant in Aberdeen WA and Big Sur CA and negative and significant in Newport OR (insignificant elsewhere).
- \* Averaged over all stations in the region, none of these three trend parameters is statistically significant.

The Pacific Coast receives considerable precipitation from Atmospheric River (AR) events which often last more than a day or two (e.g., Gershunov et al. 2017, Pan et al. 2024). The worst-known such series of events in recent history was the so-called ARek Storm that occurred between December 1861 and January 1862, which dumped nearly 10 feet of rain in parts of California and submerged the entire Central Valley for weeks under as much as 1.5 feet of water (Brewer 1930, Null and Hulbert 2007). Additionally, Paleoclimate research has found six megastorms more severe than 1861-1862 in California during the last 1800 years, occurring at intervals of 300 years or so (Porter et al. 2011).

#### SIDEBAR: Perils of short data records

San Francisco provides a good case study of the limitation of using short historical samples to characterize natural variability of extreme events. Suppose we use a 130-year sample of daily San Francisco precipitation from 1895 to 2024 and we look for 3-day, 5-day, 14-day and 30-day rainfall records. The results are as shown in Table 8-7.2.

| Event  | Record (inches) | Year |
|--------|-----------------|------|
| 3-day  | 6.94            | 2023 |
| 5-day  | 8.55            | 2023 |
| 14-day | 12.62           | 2023 |
| 30-day | 18.93           | 1998 |

Table 8-7.2: Extreme rainfall records, San Francisco, 1895-2024.

The records all cluster in the more recent data. 2023 appears to be an exceptional year and since it is near the end of the sample, it might suggest that the climate has shifted into a more hazardous state, perhaps as a result of human influences. [Note: "2023" indicates the event occurred in the water-year of Aug 2022 to Jul 2023.]

But the picture is very different if we use a sample that begins 85 years earlier, in 1850. Table 8-7.3 shows that the record-setting events then all happened in the 1860s. Furthermore 2023 is now not even in 2<sup>nd</sup> place but falls to 3<sup>rd</sup> or 4<sup>th</sup> place. Also, comparing the records of the two charts, the extreme precipitation events in 1862 and 1867 involved considerably more rainfall than the 1998 and 2023 events, with 14- and 30-day totals about 50 percent higher.

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| Event  | Record (inches) | Year | Rank of 130-yr extreme |
|--------|-----------------|------|------------------------|
| 3-day  | 8.85            | 1867 | 3                      |
| 5-day  | 9.80            | 1867 | 3                      |
| 14-day | 19.05           | 1862 | 4                      |
| 30-day | 28.25           | 1862 | 2                      |

Table 8.7.3: Extreme rainfall records, San Francisco, 1850-2024.

The range of natural variability is made even more remarkable when paleoclimate evidence is examined. Porter et al. (2011) discovered that in the past 1800 years at least six megastorms were more intense than the devastating 1861-62 ARkStorm that struck the region. Evidently such extreme events, “unprecedented” in our 1895-2024 sample, have impacted the region about every 300 years though not since 1895.

This example illustrates the limitations of using relatively short climate periods (~130 years) to assess the character and range of natural variability in general and of extreme events in particular. Accurate representation of the full range of natural variability is necessary for any attribution analyses (see 6.4). Infrastructure planners, emergency management institutions and attribution scientists would understand the significant mischaracterization of the magnitude of a future extreme if based only on the last 130 years. In this case, a single time-sample of 130 years provides an underestimation of the extreme value by up to 50% determined when adding only 45 more years of observations. Compared to millennial-scale paleoclimate evidence, an even greater underestimation would occur. An important lesson is that the climate can deliver great surprises on its own even without human influences.

We examine occurrences of 5-day deluges as follows. In a 130-year span there are 26 5-year intervals. At each location we computed the 5-day precipitation totals throughout the year and selected the 26 highest values. A single year may have more than one of the 26 heaviest. Each of those can be thought of as 1-in-5-year events. If there are no trends in precipitation then the total number of these events across all stations should be evenly spread out over the years. In Fig. 8.7.4-55.1 we show the distribution in time of these events. The deluges associated with the massive 1997-98 El Niño event are readily apparent. While erratic, as is typical of these types of precipitation metrics, there is no indication of a tendency to become more frequent over time.

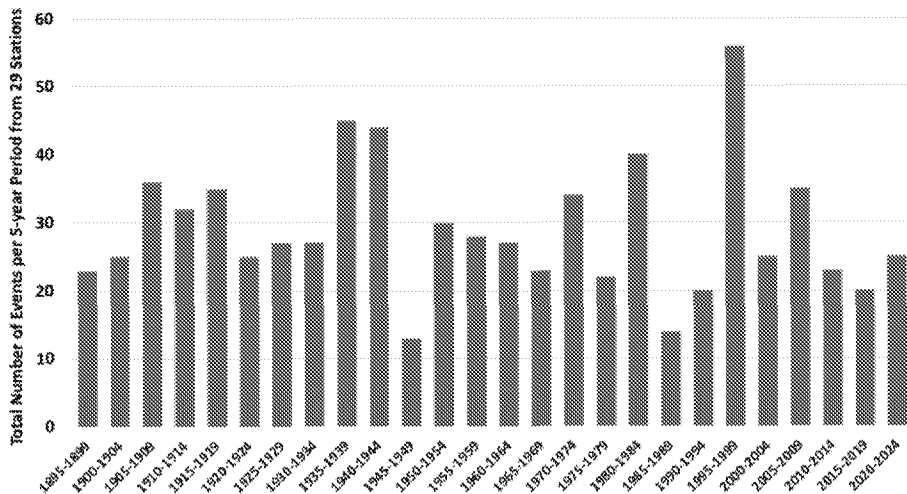


Figure 8-7.5.24-5. The time distribution by 5-year periods of the 26 heaviest occurrences for each station (i.e., nominal 1-in-5 year event) for stations along the Pacific Coast of the CONUS.

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#### *Southeast heavy rainfall events*

- \* The trend in average precipitation is positive and significant in Mobile AL and Quitman GA, and insignificant elsewhere.
- \* The trend in rainfall variance is positive and significant in Mobile AL, insignificant elsewhere.
- \* The trend in daily maximum precipitation is positive and significant in Vicksburg MS and Norfolk VA, and insignificant elsewhere.
- \* Averaged over all stations in the region none of these three trend parameters is statistically significant.

The temporal pattern of 5-day totals of the 1-in-5 yr-year heavy events in the humid Southeast (Figure 8.7.4.65.2) is generally unremarkable, though a cluster of higher values appears in 1995 to 2019. The increase in these years is due largely to the 4 northeastern-most stations of Wilmington NC, Weldon NC, Washington DC, and Norfolk VA. This confirms the pattern indicated in NCA417 and NCA523 of a tendency for an increasing frequency of heavy events, due to a temporal clustering of tropical storms from eastern NC to Maine discussed below. Otherwise, the remaining 20 stations show an unremarkable temporal distribution of heavy events.



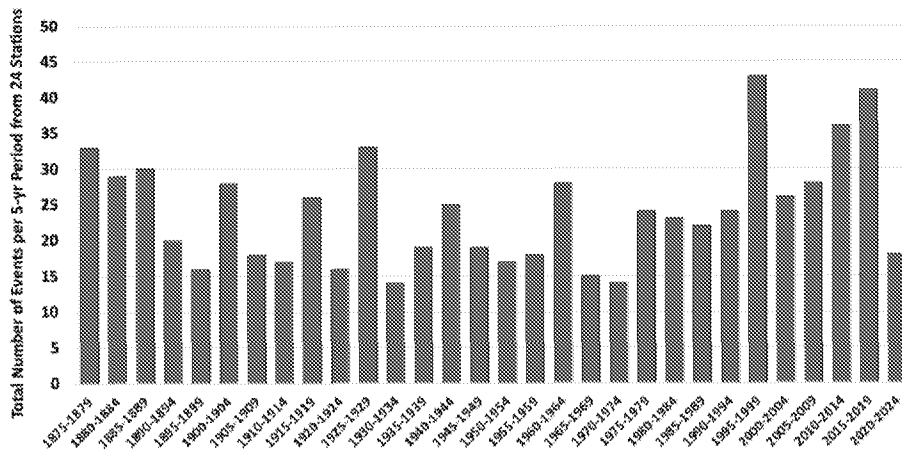


Figure 8-7.4-65.3. As above but for the 30 heaviest 1-in-5yr events for 24 stations in the humid Southeast from Austin TX to Washington DC in 5-year bins for 1875-2024.

#### Northwest heavy rainfall events

- \* The trend in average precipitation is positive and significant in 9 of 21 locations and in the region averaged overall.
- \* The trend in rainfall variance is positive and significant in Portland ME, Albany NY and Buffalo NY; insignificant elsewhere.
- \* The trend in daily maximum precipitation is positive and significant in Portland ME and Gardiner ME; insignificant elsewhere.
- \* Averaged over all stations in the region the trend parameters for variance and maximum precipitation are not statistically significant.

Fig. 8-7.4-75.3 shows the 27 (1-in-5yr) heaviest 3-day events for the last 135 years in 21 stations in the Northeast (including Montreal Canada). We use 3-day totals here as this produced the largest variations in time. In this region, 72% of the events occur during June to October and are dominated by tropical incursions of hurricanes, tropical storms or tropical storms that transition to extratropical systems. According to NCA417 and NCA523 this region experienced the largest increases in extreme events, so it shall be examined more closely.

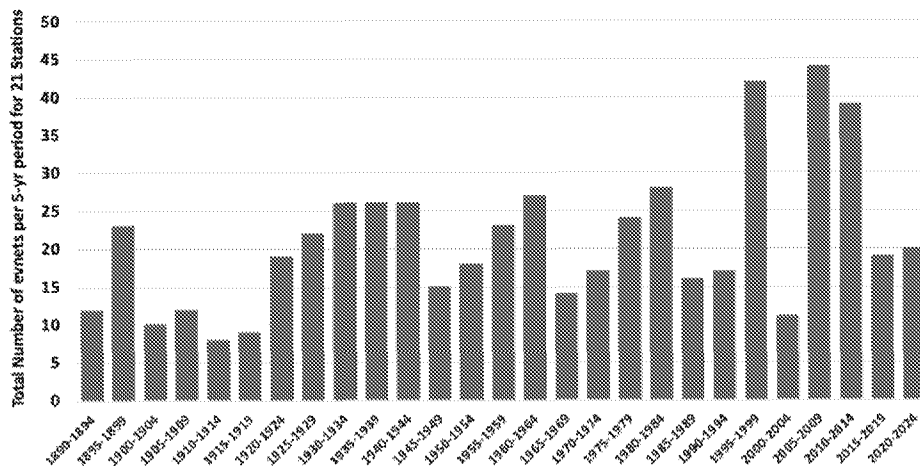


Figure 8-7.4.75.4. Time distribution of the heaviest 27 (1-in-5yr year) heaviest 3-day precipitation events for 21 stations from NY to ME, including Montreal.

Howarth et al. (2019) report differences in the Northeast-between two 18-year periods: 1979-96 and 1997-2014 (a similar region as in Fig. 8-7.4.65.4 that includes PA and NJ) of various precipitation extremes. One metric which indicated a dramatic increase (317%) was found for 24-hr events > 6 inches. This high increase is due to the very small numbers of such events of which there were only 6 in the first period and 25 in the second as reported for 58 stations. This high percentage increase is due to the very small numbers of the events: only 6 in the first period and 25 in the second. Most of the stations did not record such an event suggesting these erratic, episodic events over brief, 18-year periods, need scrutiny by additional statistical methods.

Using the information in Fig. 8-7.4.75.4 over the same years as Howarth et al. we find a 51% increase in the frequency of heavy events between the two periods. One can see in Fig. 8-7.4.65.4 that it was unfortunate that Howarth et al. ended in 2014, prior to a return to the long-term average of such events.

A feature of Howarth et al. is the use of single day totals, which is questionable because extreme events are often spread across the time-of-observation boundary. Thus stations measuring at 0700 Z am LT local time versus those at Midnight will have differing results for a particular event which would then have major impacts on counting these events. We use the 3-day totals in Fig. 8-7.4.75.45 to be sure to capture the extent of these extreme downpours. In any case, we can confirm that the period 1997 to 2014 experienced a cluster of heavier events, as Howarth et al. have documented.

Howarth's most remarkable claim (317% increase in 6" days) is potentially misleading because it is a threshold statistic (see Section section 8-4.2-8-7.3.2 above) and the ratio of small numbers over a short period. The result is not representative of *relative* extreme events for the whole region, since the majority of stations never experienced a 6" total. Figure 8-7.4.65.5.4 above determines the same number of events for each station (27 heaviest events) whose heaviest values ranged from 4.4" to 12.5" and their 27<sup>th</sup> heaviest values ranged from 3.3" to 5.0". This analysis thus allows each station to

be equally represented. In other words, if there is a region-wide increase in heavy events, it should be seen in the sum of all stations. Note too that the period of record here is 135 years vs. 36 years of Howarth et al. Except for three 5-year periods between 1995 and 2014, there is nothing statistically remarkable about the results in Fig. 8.7.4.2.

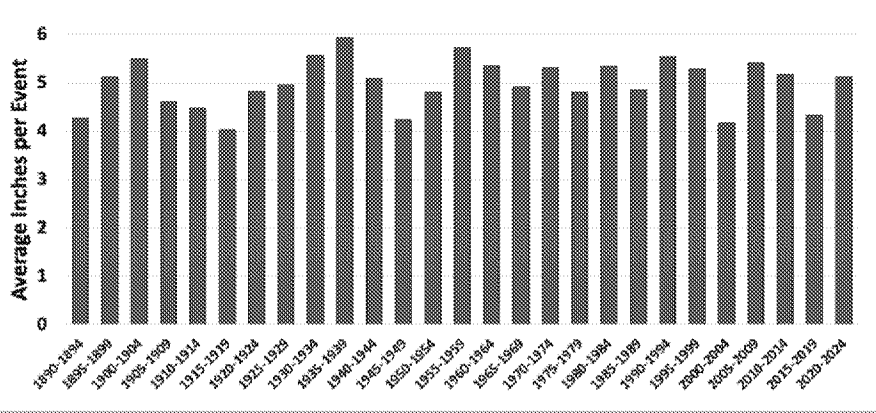


Figure 8.7.4.85.5. Average amount of precipitation falling in the 1-in-5yr events for the NE stations.

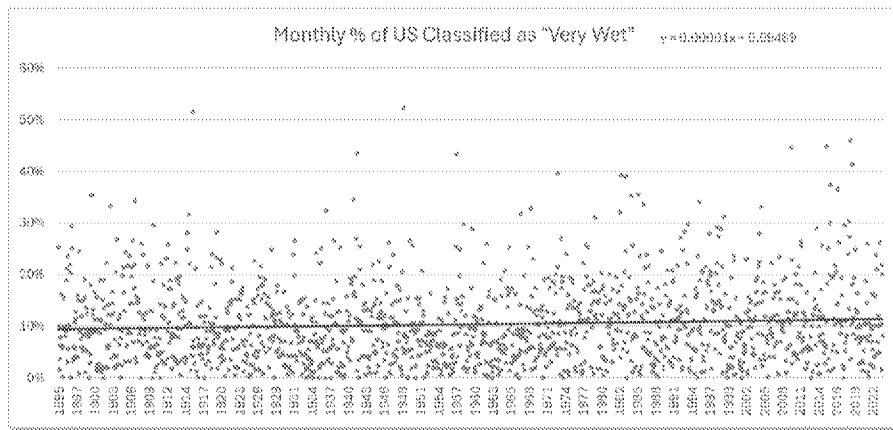
An interesting aspect of Northeast precipitation is that there has been no change in the amount of precipitation per heaviest event, as shown in Fig. 8.7.4.85.5. The trend is only +0.02"/decade. The highest amount, 1935-39, includes the Great New England Hurricane of 1938, one of the rare major (Category 3 or higher) hurricanes to strike the region. The results in Figs. 8.7.4.45.4 and 8.7.4.25.5 suggest that though there was an uptick in the number of events during the period 1995 to 2014, the events individually are not becoming more intense.

long et al. (2024) document the increase of tropical influences on precipitation events in the Northeast since 1959 and concluded, "The autumn extreme precipitation trend over the Northeast US is primarily attributed to tropical cyclone-related events since the 1990s." The question then becomes, was the temporal clustering of tropical systems in 1997-2014 which affected the Northeast a response to increasing GHGs (see Chapter 9 Attribution)? long et al. examined CMIP-6 model output which suggests that there will be fewer such systems in the 21st century but that the intensity of the rainfall events might increase. This conjecture is not seen in Fig. 8.7.4.75.5 where the amount-per-event has remained steady over the 135-year period.

~~For substantial urban areas~~ There is some evidence to indicate the heaviest rainfall events may be redistributed due to the impact urban infrastructure has on the local weather (e.g., Pielke Sr. et al. 2011, Zhang et al. 2018, Yang et al. 2024). Yang et al. state, "Cities that experience compact development tend to witness larger increases in extreme rainfall frequency over downtown than their rural surroundings, while the anomalies in extreme rainfall frequency diminish for cities with

dispersed development." While this is an important insight to consider, the effect on the specific stations used in this analysis is unknown, or at least not detectable in Fig. 8.7.4.25.5.

In summary, the evidence from the historical record of extreme precipitation events in the CONUS is generally not consistent from region to region so that inferences regarding trends and their projections are wrought with significant uncertainty. In most regions and perhaps all, it is our analysis here opinion suggests that given the very nature of the erratic and episodic character of extreme precipitation events, changes that can be confidently categorized as significant relative to natural variability have not been observed renders the discovery of statistically significant changes, including a relationship to CO2 concentrations, a result yet to be achieved (McKirk and Christy 2019).



#### 8.7.6 Tornadoes

AR6: [O]bservational trends in tornadoes, hail, and lightning associated with severe convective storms are **not robustly detected** due to insufficient coverage of the long-term observations. There is *medium confidence* that the mean annual number of tornadoes in the USA has remained relatively constant. (Chapter 11, section 11.7.3, p. 1594)

As noted, there is no evidence of trends in US tornadoes or extreme convective storms.

Figure 8.3.84-1: Long-term US wetness (%). Source: NOAA [HYPERLINK "<https://www.ncei.noaa.gov/access/monitoring/uspa/wet-dry/0>"]

#### 9.7.2.27 Flooding

Changes in floods were assessed as follows:

AR6: "The SREX assessed *low confidence* for observed changes in the magnitude or frequency of floods at the global scale. This assessment was confirmed by the AR5 report. The SR1.5 found increases in flood frequency and extreme streamflow in some regions, but decreases in other regions. . . . [H]ydrological literature on observed flood changes is heterogeneous, focusing at regional and sub-regional basin scales, making it difficult to synthesise at the global and sometimes regional scales." (Chapter 11.5)

AR6: "The seasonality of floods has changed in cold regions where snowmelt dominates the flow regime in response to warming (*high confidence*). Confidence about peak flow trends over past decades on the global scale is *low*." (Chapter 11.5)

NCA17: "Trends in extreme high values of streamflow are mixed across the United States. Analysis of 200 U.S. stream gauges indicates areas of both increasing and decreasing flooding magnitude but does not provide robust evidence that these trends are attributable to human influences" (pp. 240-241)

The absence of detectable US-wide trends in flooding is consistent with the findings in the previous section of absence of coherent changes in extreme precipitation.

SREX (p. 176)

In the United States and Canada during the 20th century and in the early 21st century, there is no compelling evidence for climate-driven changes in the magnitude or frequency of floods.

AR5 (p. 214)

AR4 WGI Chapter 3 (Trenberth et al., 2007) did not assess changes in floods but AR4 WGI concluded that there was not a general global trend in the incidence of floods (Kundzewicz et al., 2007). SREX went further to suggest that there was low agreement and thus *low confidence* at the global scale regarding changes in the magnitude or frequency of floods or even the sign of changes.

AR5 WGI assesses floods in regional detail accounting for the fact that trends in floods are strongly influenced by changes in river management (see also Section 2.5.2). Although the most evident flood trends appear to be in northern high latitudes, where observed warming trends have been largest, in some regions no evidence of a trend in extreme flooding has been found, for example, over Russia based on daily river discharge (Shildomanov et al., 2007). Other studies for Europe (Hennaford and Marsh, 2008; Renard et al., 2009; Petrow and Mery,

2009; Stahl et al., 2010) and Asia (Jiang et al., 2008; Delgado et al., 2010) show evidence for upward, downward or no trend in the magnitude and frequency of floods, so that there is currently no clear and widespread evidence for observed changes in flooding except for the earlier spring flow in snow-dominated regions (Seneyratne et al., 2012). In summary, there continues to be a lack of evidence and thus *low confidence* regarding the sign of trend in the magnitude and/or frequency of floods on a global scale.

#### AR6 (Ch. 11 p. 1540)

The SR5X (Seneyratne et al., 2012) assessed *low confidence* for observed changes in the magnitude or frequency of floods at the global scale. This assessment was confirmed by the AR5 report (Hartmann et al., 2013). The SR15 (Moggh-Guldberg et al., 2018) found increases in flood frequency and extreme streamflow in some regions, but decreases in other regions. While the number of studies on flood trends has increased since the AR5 report, and there were also new analyses after the release of SR15 (Berghuijs et al., 2017; Blöschl et al., 2019; Gudmundsson et al., 2019), hydrological literature on observed flood changes is heterogeneous, focusing at regional and sub-regional basin scales, making it difficult to synthesise at the global and sometimes regional scales.

In summary, the seasonality of floods has changed in cold regions where snowmelt dominates the flow regime in response to warming (*high confidence*). Confidence about peak flow trends over past decades on the global scale is *low*, but there are regions experiencing increases, including parts of Asia, southern South America, the northeast USA, northwestern Europe, and the Amazon, and regions experiencing decreases, including parts of the Mediterranean, Australia, Africa, and the southwestern USA.

#### US NCA17 pp. 240-41:

"The IPCC AR5 did not attribute changes in flooding to anthropogenic influence nor report detectable changes in flooding magnitude, duration, or frequency. Trends in extreme high values of streamflow are mixed across the United States. Analysis of 200 U.S. stream gauges indicates areas of both increasing and decreasing flooding magnitude, but does not provide robust evidence that these trends are attributable to human influences."

The complex mix of processes complicates the formal attribution of observed flooding trends to anthropogenic climate change and suggests that additional scientific rigor is needed in flood attribution studies. As noted above, precipitation increases have been found to strongly influence changes in flood statistics. However, in U.S. regions, no formal attribution of precipitation changes to anthropogenic forcing has been made so far, so indirect attribution of flooding changes is not possible. Hence, no formal attribution of observed flooding changes to anthropogenic forcing has been claimed."

### 8.2.3 Heatwaves

#### AR5 (p. 212 WG1)

Table 2.13 shows that there has been a *likely* increasing trend in the frequency of heatwaves since the middle of the 20th century in Europe and Australia and across much of Asia where there are sufficient data. However, confidence on a global scale is *medium* owing to lack of studies over Africa and South America but also in part owing to differences in trends depending on how heatwaves are defined (Perkins et al., 2012). Using monthly means as a proxy for heatwaves Gougeon et al. (2013) and Hansen et al. (2012) indicate that record-

breaking temperatures in recent decades substantially exceed what would be expected by chance; but caution is required when making inferences between these studies and those that deal with multi-day events and/or use more complex definitions for heatwave events. There is also evidence in some regions that periods prior to the 1950s had more heatwaves (e.g., over the USA, the decade of the 1930s stands out and is also associated with extreme drought conditions (Peterson et al., 2013)) whereas conversely in other regions heatwave trends may have been underestimated owing to poor quality and/or consistency of data (e.g., Della Morte et al. (2007a) over Western Europe; Kuglitich et al. (2009, 2010) over the Mediterranean). Recent available studies also suggest that the number of cold spells has reduced significantly since the 1950s (Donat et al., 2013a, 2013c).

In summary, new analyses continue to support the AR4 and SREX conclusions that since about 1950 it is *very likely* that the numbers of cold days and nights have decreased and the numbers of warm days and nights have increased overall on the global scale; that is, for land areas with sufficient data. It is *likely* that such changes have also occurred across most of North America, Europe, Asia and Australia.

#### NCA12 (pp. 190-191)

Changes in warm extremes are more nuanced than changes in cold extremes. For instance, the warmest daily temperature of the year increased in some parts of the West over the past century (Figure 6.2), but there were decreases in almost all locations east of the Rocky Mountains. In fact, all eastern regions experienced a net decrease (Table 6.2), most notably the Midwest (about 2.2°F [1.2°C]) and the Southeast (roughly 1.5°F [0.8°C]). The decreases in the eastern half of the Nation, particularly in the Great Plains, are mainly tied to the unprecedented summer heat of the 1930s Dust Bowl era, which was exacerbated by land-surface feedbacks driven by springtime precipitation deficits and land mismanagement. However, anthropogenic aerosol forcing may also have reduced summer temperatures in the Northeast and Southeast from the early 1950s to the mid-1970s, and agricultural intensification may have suppressed the hottest extremes in the Midwest.

Since the mid-1960s, there has been only a very slight increase in the warmest daily temperature of the year (amidst large interannual variability). Heat waves (6-day periods with a maximum temperature above the 90th percentile for 1961–1990) increased in frequency until the mid-1920s, became considerably less common through the mid-1960s, and increased in frequency again thereafter (Figure 6.4). As with warm daily temperatures, heat wave magnitude reached a maximum in the 1930s.

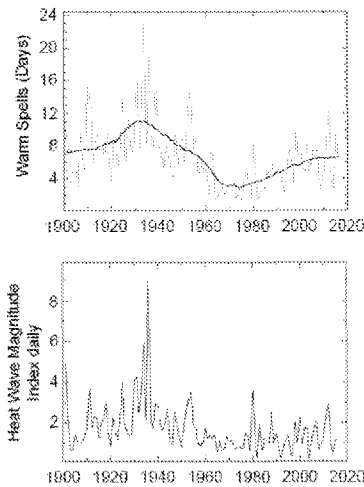


Figure 8.2.1: US Heat waves since 1900. Source: NCA17 Figure 6.4

AR6 (p. 1550)

In North America (Table 11.19), there is very robust evidence for a *very likely* increase in the intensity and frequency of hot extremes and decrease in the intensity and frequency of cold extremes for the whole continent, though there are substantial spatial and seasonal variations in the trends. Minimum temperatures display warming consistently across the continent, while there are more contrasting trends in the annual maximum daily temperatures in parts of the USA (Figure 11.9; Lee et al., 2014; van Oldenborgh et al., 2019; Dunn et al., 2020).

#### 8.2.4 Extreme snowfall events

Note: extreme snowfall events in the US northeast are assessed in relation to winter Extratropical Cyclone (ETC) activity.

AR6 Ch 11, p. 1593

There is *high confidence* that snowfall associated with winter ETCs will decrease in the future, because increases in tropospheric temperatures lead to a lower proportion of precipitation falling as snow (O’Gorman, 2014; Rhoades et al., 2018; Zarzycki, 2018). However, there is *medium confidence* that extreme snowfall events associated with winter ETCs will change little in regions where snowfall will be supported in the future (O’Gorman, 2014; Zarzycki, 2018).

#### 8.2.5 Extreme precipitation



#### SREX (p. 143)

Recent studies have updated the assessment of the AR4, with more regional results now available (Table 3-2). Overall, this additional evidence confirms that more locations and studies show an increase than a decrease in extreme precipitation, but that there are also wide regional and seasonal variations, and trends in many regions are not statistically significant (Table 3-2). Based on station data from Canada, the United States, and Mexico, Peterson et al. (2008a) reported that heavy precipitation has been increasing over 1950–2004, as well as the average amount of precipitation falling on days with precipitation.

#### AR5 (pp. 212–14)

In summary, further analyses continue to support the AR4 and SREX conclusions that it is likely that since 1951 there have been statistically significant increases in the number of heavy precipitation events (e.g., above the 95th percentile) in more regions than there have been statistically significant decreases, but there are strong regional and subregional variations in the trends. In particular, many regions present statistically non-significant or negative trends, and, where seasonal changes have been assessed, there are also variations between seasons (e.g., more consistent trends in winter than in summer in Europe). The overall most consistent trends towards heavier precipitation events are found in central North America (very likely increases) but assessment for Europe shows likely increases in more regions than decreases.

#### AR6 (p. 1560)

In North America, there is robust evidence that the magnitude and intensity of extreme precipitation has very likely increased since the 1950s. Both [one-day maximum and 15-day maximum] have significantly increased in North America during 1950–2012 (Sun et al., 2020, also Figure 11.11). There is, however, regional diversity. In Canada, there is a lack of detectable trends in observed annual maximum daily (or shorter duration) precipitation (Shephard et al., 2014; Makis et al., 2015; Vincent et al., 2016).

#### NC417 pp. 213–14

Detectability of trends (compared to internal variability) for a number of precipitation metrics over the continental United States has been examined; however, trends identified for the U.S. regions have not been clearly attributed to anthropogenic forcing. One study concluded that increasing precipitation trends in some north-central U.S. regions and the extreme annual anomalies there in 2013 were at least partly attributable to the combination of anthropogenic and natural forcing. Based on current evidence, it is concluded that detectable but not attributable increases in mean precipitation have occurred over parts of the central United States. Formal detection-attribution studies indicate a human contribution to extreme precipitation increases over the continental United States, but confidence is low based on those studies alone due to the short observational period, high natural variability, and model uncertainty.

In summary, based on available studies, it is concluded that for the continental United States there is high confidence in the detection of extreme precipitation increases, while there is low confidence in attributing the extreme precipitation changes purely to anthropogenic forcing.

#### 8.2.6 Tornadoes and severe convective storms

Severe convective storms are convective systems that are associated with extreme phenomena such as tornadoes, hail, heavy precipitation (rain or snow), strong winds, and lightning.

The assessment of changes in severe convective storms in SREX (Chapter 3, Seneviratne et al., 2012) and AR5 (Chapter 12, Collins et al., 2013) is limited and focused mainly on tornadoes and hail storms. The SREX assessed that there is *low confidence in observed trends in tornadoes and hail* because of data inhomogeneities and inadequacies in monitoring systems. Subsequent literature assessed in the Climate Science Special Report (Kossin et al., 2017) led to the assessment of the observed tornado activity over the 2000s in the USA, with a decrease in the number of days per year with tornadoes and an increase in the number of tornadoes on these days (*medium confidence*). However, there is *low confidence in past trends for hail and severe thunderstorm winds*. Climate models consistently project environmental changes that would support an increase in the frequency and intensity of severe thunderstorms that combine tornadoes, hail, and winds (*high confidence*), but there is *low confidence* in the details of the projected increase.

In summary, because the definition of severe convective storms varies depending on the literature and the region, it is not straightforward to make a synthesizing view of observed trends in severe convective storms in different regions. In particular, observational trends in tornadoes, hail, and lightning associated with severe convective storms are not robustly detected due to insufficient coverage of the long-term observations. There is *medium confidence* that the mean annual number of tornadoes in the USA has remained relatively constant, but their variability of occurrence has increased since the 1970s, particularly over the 2000s, with a decrease in the number of days per year and an increase in the number of tornadoes on these days (*high confidence*). Detected tornadoes have also increased in Europe, but the trend depends on the density of observations.

In summary, it is extremely difficult to detect and attribute changes in severe convective storms. There is limited evidence that extreme precipitation associated with severe convective storms has increased in some cases.

## 8.2.7 Hurricanes and Tropical Cyclones

SREX (p. 150):

There have been no significant trends observed in global tropical cyclone frequency records, including over the present 40-year period of satellite observations (e.g., Webster et al., 2005). Regional trends in tropical cyclone frequency have been identified in the North Atlantic, but the fidelity of these trends is debated (Holland and Webster, 2007; Landsea, 2007; Mann et al., 2007a). Different methods for estimating undercounts in the earlier part of the North Atlantic tropical cyclone record provide mixed conclusions (Chang and Gao, 2007; Mann et al., 2007b; Kunkel et al., 2008; Vecchi and Knutson, 2008). Regional trends have not been detected in other oceans (Chan and Xu, 2009; Kubota and Chan, 2009; Callaghan and Power, 2011). It thus remains uncertain whether any observed increases in tropical cyclone frequency on time scales longer than about 40 years are robust after accounting for past changes in observing capabilities (Knutson et al., 2010).

AR5 (pp. 316–17):

Current data sets indicate no significant observed trends in global tropical cyclone frequency over the past century and it remains uncertain whether any reported long-term increases in tropical cyclone frequency are robust after accounting for past changes in observing capabilities (Knutson et al., 2010). No robust trends in annual numbers of tropical storms, hurricanes and major hurricanes counts have been identified over the past 100 years in the North Atlantic basin. Measures of land-falling tropical cyclone frequency (Figure 2.24) are generally considered to be more reliable than counts of all storms which tend to be strongly influenced by those that are weak and/or short-lived. Callaghan and Power (2011) find a statistically significant decrease in Eastern Australia land-falling tropical cyclones since the late 19th century although including 2010/2011 season data this trend becomes non-significant (i.e., a trend of zero lies just inside the 90% confidence interval). Significant trends are not found in other oceans on shorter time scales (Chan and Xu, 2009; Kubota and Chan, 2009; Mohapatra et al., 2011; Weinkle et al., 2012), although Grinstead et al. (2012) find a significant positive trend in eastern USA using tide gauge data from 1923–2009 as a proxy for storm surges associated with land-falling hurricanes. Differences between tropical cyclone studies highlight the challenges that still lie ahead in assessing long-term trends.

In summary, this assessment does not revise the SREX conclusion of low confidence that any reported long-term (centennial) increases in tropical cyclone activity are robust after accounting for past changes in observing capabilities. More recent assessments indicate that it is *unlikely* that annual numbers of tropical storms, hurricanes and major hurricanes counts have increased over the past 100 years in the North Atlantic basin. Evidence, however, is for a virtually certain increase in the frequency and intensity of the strongest tropical cyclones since the 1970s in that region.

AR6 (p.1525)

There is low confidence in most reported long-term (multidecadal to centennial) trends in TC frequency or intensity-based metrics due to changes in the technology used to collect the best-track data. This should not be interpreted as implying that no physical (real) trends exist, but rather as indicating that either the quality or the temporal length of the data is not adequate to provide robust trend detection statements, particularly in the presence of multidecadal variability.

There are previous and ongoing efforts to homogenize the best-track data (Elsner et al., 2008; Kossin et al., 2013, 2020; Choy et al., 2015; Landsea, 2015; Emanuel et al., 2018) and there is substantial literature that finds positive trends in intensity-related metrics in the best-track during the “satellite period”, which is generally limited to the past ~40 years (Kang and Elsner, 2012; Kishitawala et al., 2012; Kossin et al., 2013, 2020; Mei and Xie, 2016; Zhao et al., 2018; Tawale and Touboli, 2019). When best-track trends are tested using homogenized data, the intensity trends generally remain positive, but are smaller in amplitude (Kossin et al., 2013; Holland and Bruyere, 2014). Kossin et al. (2020) extended the homogenized TC intensity record to the period 1979–2017 and identified significant global increases in major TC exceedance probability of about 6% per decade. In

<sup>6</sup>The underlined text referenced a study (Kossin et al. 2020) that later retracted a portion of its findings. Those authors assembled a data set on global TC incidence spanning 1979 to 2017 from which they claimed that the global fraction of TCs reaching major damage (Cat 3–5) rose from 2.7% during 1979–1992 to 3.1% during 1996–2017 and that the increase was statistically significant. However, closer examination of their results showed a significant increase only in the North Atlantic (1.6% to 3.4%) whereas change in all other basins (Eastern

addition to trends in TC intensity, there is evidence that TC intensification rates and the frequency of rapid intensification events have increased within the satellite era (Kishtawal et al., 2012; Balaguru et al., 2018; Bhatia et al., 2018). The increase in intensification rates is found in the best tracks as well as the homogenized intensity data.

~~A subset of the best-track data corresponding to hurricanes that have directly impacted the United States since 1900 is considered to be reliable, and shows no trend in the frequency of U.S. landfall events (Knutson et al., 2019).~~

### 8.7.2.868 Droughts

Assessments of drought trends were as follows:

AR6: "Few AR6 regions show observed increases in meteorological drought" (Section 11.9, p. 1575).

AR6: "Increasing trends in agricultural and ecological droughts have been observed on all continents (*medium confidence*), but decreases only in one AR6 region (*medium confidence*). Increasing trends in hydrological droughts have been observed in a few AR6 regions." (Chapter 11 Summary)

NCA17: "As a consequence of this increased precipitation, drought statistics over the entire CONUS have declined." (p. 233)

NCA17: "Recent droughts and associated heat waves have reached record intensity in some regions of the United States; however, by geographical scale and duration, the Dust Bowl era of the 1930s remains the benchmark drought and extreme heat event in the historical record (very high confidence)." (p. 231)

SREX: "From a paleoclimate perspective, recent droughts are not unprecedented, with severe 'megadroughts' reported in the paleoclimatic record for Europe, North America, and Australia." (p. 170)

US NCA17 REPORT (Ch. 8, Wehner et al. 2017)  
p. 231:

Recent droughts and associated heat waves have reached record intensity in some regions of the United States; however, by geographical scale and duration, the Dust Bowl era of the 1930s remains the benchmark drought and extreme heat event in the historical record (very high confidence). While by some measures drought has decreased over much of the continental United States in association with long-term increases in precipitation,

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*Red Sea, Western Pacific, North Indian, South Indian, South Pacific) were not statistically significant in a subsequent correction ([HYPERLINK "<https://www.pnas.org/doi/10.1073/pnas.2021573117>"]. Kossin et al. stated that the global probability of observing a major TC rose from 24% during 1979-1997 to 27% in the same period and that the evidence for statistical significance was now weaker. Nevertheless, the authors claimed that the correction did not affect their conclusions.*

neither the precipitation increases nor inferred drought decreases have been confidently attributed to anthropogenic forcing.

The human effect on recent major U.S. droughts is complicated. Little evidence is found for a human influence on observed precipitation deficits, but much evidence is found for a human influence on surface soil moisture deficits due to increased evapotranspiration caused by higher temperatures. (High confidence)

p. 232:

Drought is, of course, directly connected to seasonal precipitation totals. Figure 7-1 shows detectable observed recent changes in seasonal precipitation. In fact, the increases in observed summer and fall precipitation are at odds with the projections in Figure 7-5. As a consequence of this increased precipitation, drought statistics over the entire CONUS have declined.

SREX (p. 170)

From a paleoclimate perspective recent droughts are not unprecedented, with severe 'megadroughts' reported in the paleoclimatic record for Europe, North America, and Australia (Jansen et al., 2007). Recent studies extend this observation to African and Indian droughts (Sinha et al., 2007; Shanshan et al., 2009); much more severe and longer droughts occurred in the past centuries with widespread ecological, political, and socioeconomic consequences. Overall, these studies confirm that in the last millennium several extreme droughts have occurred (Brède and Badeau, 2008; Kuttig, 2008; Rüntgen et al., 2010).

In North America, there is *medium confidence* that there has been an overall slight tendency toward less dryness (wetting trend with more soil moisture and runoff Table 3-2), although analyses for some subregions also indicate tendencies toward increasing dryness. This assessment is based on several lines of evidence, including simulations with different hydrological models as well as PDSI and GDD estimates (Alexander et al., 2006; Andreadis and Lettenmaier, 2006; van der Schrier et al., 2006a; Kunkel et al., 2008; Sheffield and Wood, 2008a; Dai, 2011).

The most severe droughts in the 20th century have occurred in the 1930s and 1950s, where the 1930s Dust Bowl was most intense and the 1950s drought most persistent (Andreadis et al., 2005) in the United States, while in Mexico the 1950s and late 1990s were the driest periods. Recent regional trends toward more severe drought conditions were identified over southern and western Canada, Alaska, and Mexico, with subregional exceptions (Dai, 2011).

SREX (p. 172)

Overall, though new studies have furthered the understanding of the mechanisms leading to drought, there is still relatively limited evidence to provide an attribution of observed changes, in particular given the issues associated with the availability of observational data (Section 3.2.1) and the definition and computation of drought indicators (Box 3-3). This latter point was mostly identified in post-AR4 studies (Box 3-3). Moreover, regions where consistent increases in drought are identified (see 'Observed Changes') are only partly consistent with those where projections indicate an enhancement of drought conditions in coming decades (see next paragraph). We thus assess that there is *medium confidence* (see also Section 3.1.5) that anthropogenic influence has contributed to some

changes in the drought patterns observed in the second half of the 20<sup>th</sup> century, based on its attributed impact on precipitation and temperature changes (though temperature can only be indirectly related to drought trends; see Box 3-3). However there is low confidence in the attribution of changes in droughts at the level of individual regions.

#### AR5 (pp. 214-215)

Based on evidence since AR4, SREX concluded that there were not enough direct observations of dryness to suggest high confidence in observed trends globally, although there was medium confidence that since the 1950s some regions of the world have experienced more intense and longer droughts. The differences between AR4 and SREX are due primarily to analyses post-AR4, differences in how both assessments considered drought and updated IPCC uncertainty guidance.

Because drought is a complex variable and can at best be incompletely represented by commonly used drought indices, discrepancies in the interpretation of changes can result. For example, Sheffield and Wood (2008) found decreasing trends in the duration, intensity and severity of drought globally. Conversely, Dai (2011a,b) found a general global increase in drought, although with substantial regional variation and individual events dominating trend signatures in some regions (e.g., the 1970s prolonged Sahel drought and the 1930s drought in the USA and Canadian Prairies). Studies subsequent to these continue to provide somewhat different conclusions on trends in global droughts and/or dryness since the middle of the 20<sup>th</sup> century (Sheffield et al., 2012; Dai, 2013; Donat et al., 2013c; van der Schrier et al., 2013).

In summary, the current assessment concludes that there is not enough evidence at present to suggest more than low confidence in a global-scale observed trend in drought or dryness (lack of rainfall) since the middle of the 20<sup>th</sup> century, owing to lack of direct observations, geographical inconsistencies in the trends, and dependence of inferred trends on the index choice. Based on updated studies, AR4 conclusions regarding global increasing trends in drought since the 1970s were probably overstated. However, it is likely that the frequency and intensity of drought has increased in the Mediterranean and West Africa and decreased in central North America and north-west Australia since 1950.

#### AR6 (Drought, Observed trends, Section 11.6.2, pp. 1572-75)

##### p-1572

Strong precipitation deficits have been recorded in recent decades in the Amazon (2005-2010), south-western China (2009-2010), south-western North America (2011-2014), Australia (1997-2009), California (2014), the middle East (2012-2016), Chile (2010-2015), the Great Horn of Africa (2011), among others (van Dijk et al., 2013; Mann and Gleick, 2015; Rowell et al., 2015; Marengo and Espinoza, 2016; Dai and Zhao, 2012; Garreaud et al., 2012, 2020; Marengo et al., 2017; Brito et al., 2018; Cook et al., 2018). Global studies generally show no significant trends in SPI time series (Orlowsky and Senaviratne, 2013; Spinoni et al., 2014), and in derived drought frequency and severity data (Spinoni et al., 2019), with very few regional exceptions (Section 11.9 and Figure 11.17).

##### p-1574

For AR6 regions, several studies suggest an increase in the frequency and areal extent of soil moisture deficits, with examples in East Asia (Cheng et al., 2015; Y. Qin et al., 2015; Jia et al., 2019), Western and Central Europe (Trnka et al., 2015b), and the Mediterranean (Hanel et

al., 2018; Moravec et al., 2019; Markonis et al., 2021). Nonetheless, some analyses also show no long-term trends in soil drying in some AR6 regions—for example, in Eastern North America (Park Williams et al., 2017) and Central North America (Senger et al., 2019), as well as in North Eastern Africa (Kew et al., 2021).

There is evidence based on streamflow records of increased hydrological droughts in East Asia (D. Zhang et al., 2018) and southern Africa (Gudmundsson et al., 2019). In areas of Western and Central Europe and Northern Europe, there is no evidence of changes in the severity of hydrological droughts since 1950 based on flow reconstructions (Gillieset et al., 2017; Barker et al., 2019) and observations (Vicente-Serrano et al., 2019). In North America, depending on the methods, datasets and study periods, there are differences between studies that suggest an increase (Shukla et al., 2015; Udall and Overpeck, 2017) versus a decrease in hydrological drought frequency (Mo and Lettenmaier, 2018), but in general there is strong spatial variability (Pashiri and Pol, 2016). Streamflow observation reference networks of near-natural catchments have also been used to isolate the effect of climate trends on hydrological drought trends in a few regions, but these show limited trends in Northern Europe and Western and Central Europe (Stahl et al., 2010; Bard et al., 2015; Harrigan et al., 2018), North America (Dudley et al., 2020) and most of Australia, with the exception of Eastern and Southern Australia (X.S. Zhang et al., 2016).

p.1575

Few AR6 regions show observed increases in meteorological drought (Section 11.9), mostly in Africa and South America (NES; *high confidence*; WAF, CAE, ESAF, SAM, SMS, SSA, SAS; *medium confidence*); a few others show a decrease (WSB, ESE, NAL, CAU, NEU, CNA; *medium confidence*). There are stronger signals indicating observed increases in agricultural and ecological drought (Section 11.9), which highlights the role of increased [evapotranspiration] driven by increased [atmospheric evaporative demand] for these trends (Sections 11.6.2.3, 11.6.2.5). Past increases in agricultural and ecological droughts are found on all continents and several regions (WAF, CAE, WSAR, ESAF, WCA, ECA, EAS, SALL, MED, WCE, NES; *medium confidence*), while decreases are found only in one AR6 region (NAL; *medium confidence*). The more limited availability of datasets makes it more difficult to assess historical trends in hydrological drought at regional scale (Section 11.9). Increasing (MED; *high confidence*; WAF, EAS, SALL; *medium confidence*) and decreasing (NEU, SES; *medium confidence*) trends in hydrological droughts have only been observed in a few regions.

AR6 on Attribution (p.1577)

There are only two AR6 regions in which there is at least *medium confidence* that human-induced climate change has contributed to changes in meteorological droughts (Section 11.9). In South-western South America (SSW), there is *medium confidence* that human-induced climate change has contributed to an increase in meteorological droughts (Boitier et al., 2016; Garreaud et al., 2020), while in Northern Europe (NEU), there is *medium confidence* that it has contributed to a decrease in meteorological droughts (Gudmundsson and Senewiratne, 2016) (Section 11.9). In other AR6 regions, there is inconclusive evidence in the attribution of long-term trends, but a human contribution to single meteorological events or subregional trends has been identified in some instances. In North America, the human influence on precipitation deficits is complex (Wehner et al., 2017), with low confidence in the attribution of long-term changes in meteorological drought in AR6 regions.

As shown in Figure 8.7.3-96B.1, US long term data (NOAA) shows an insignificantly declining tendency toward extreme dryness (-0.001% per year)

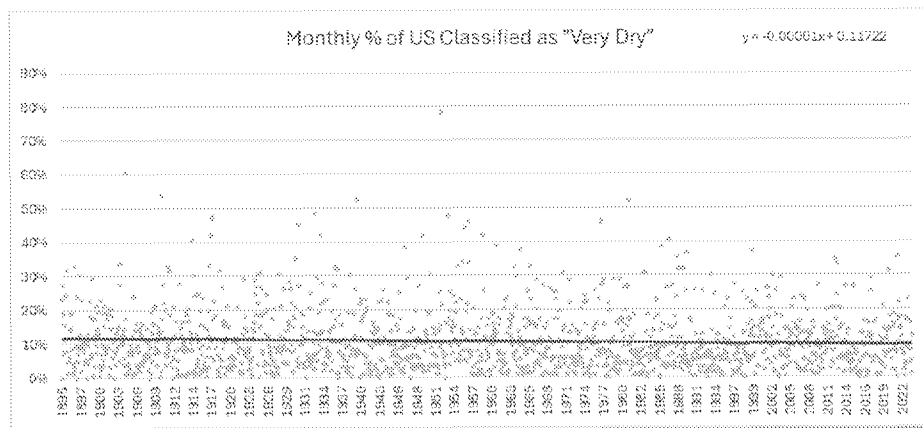


Figure 8.7.3-96B.1: US dryness (%) 1895–2023. Source: NOAA [HYPERLINK "<https://www.ncei.noaa.gov/access/monitoring/uspa/wet-dry/0/>"]

Kogan et al. (2020) examines a 38-year high-resolution satellite-based drought measure and concludes that global drought has not intensified and is not connected to climate change: "it is possible to state firmly that global and main grain countries' drought area and intensity trends have not been following global climate warmings since 1980's."

## 8.32 Extreme weather trends at global and continental indicators of scale extreme weather trends

### 8.32.1 Tropical Cyclones (TCs)

Hurricane strength records for the North Atlantic and the Western Pacific go back to 1850 and the record does not show an increase in either total or major TCs. Figure 8.3.1 was published by Roger Pielke Jr. as an update to the Best Track data series originally presented in Weinko et al. (2012).



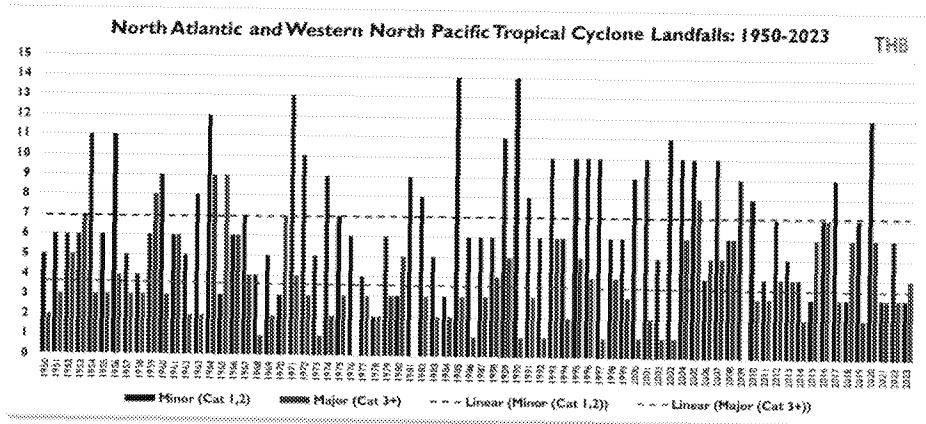


Figure 8.3.1. Tropical Cyclone Landfalls. Source: [HYPERLINK "https://rogerpielkejr.substack.com/p/global-tropical-cyclones"], Weinko et al. (2012)

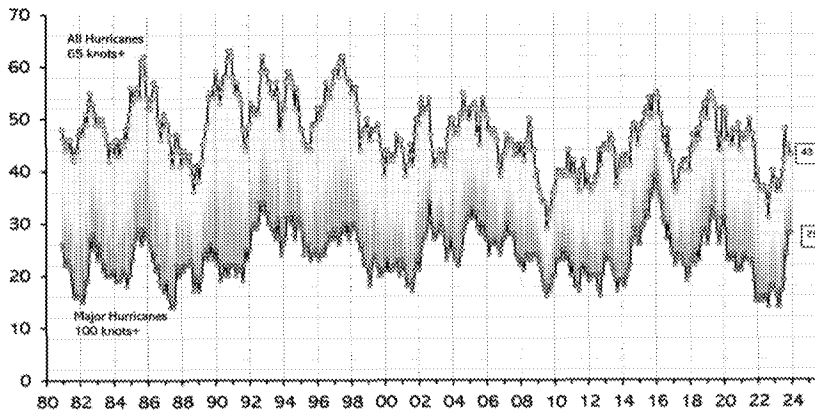
Similarly, after 1980, as shown in Figure 8.3.2, (Maue 2025, [HYPERLINK "https://climatlas.com/tropical/"]) shows that, which reproduces data from the Climate Atlas of Dr. Ryan Maue both the total number of hurricanes and the frequency of major ones hurricanes have not become more common since 1980, the period of rapidly growing human influences. In fact, both numbers have trended down slightly since the 1990s:

Commented [A8]: Climate Atlas of Dr. Ryan Maue

Global Major Hurricane Frequency – 12 month running sums – @RyanMaue

Updated December 31, 2023

Last 30-years: 45.7 H | 24.4 M



Global Major Hurricane Frequency – 12 month running sums – @RyanMaue

Updated March 10, 2025

Last 30-years, annual: 45 H | 24 M

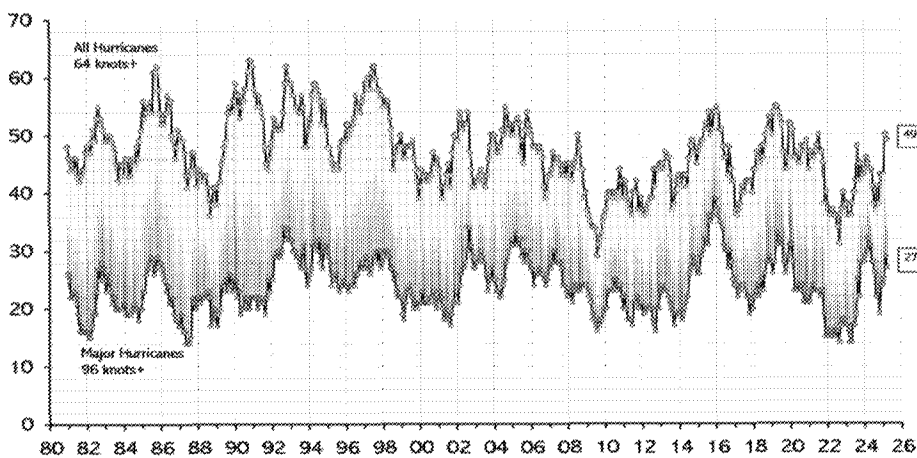


Figure 8.2.2: Global hurricane frequency. Source: Maue (2024/2025)

A metric that combines the number, duration, and frequency strength of TCs is the Accumulated Cyclone Energy (or ACE) Index maintained at Colorado State University, shown in Figure 8.2.3. As is clear, it is also not clearly shows no long-term increase, in fact declining slightly and since 1990 has declined slightly.

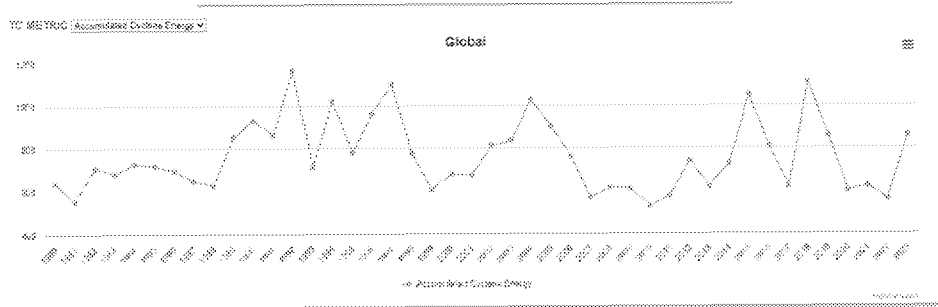


Figure 8.3.3: Global Accumulated Cyclone Energy. Source: Klotzbach (2025)

[HYPERLINK "<https://tropical.atmos.colostate.edu/Realtime/index.php?arch&loc=global>"]

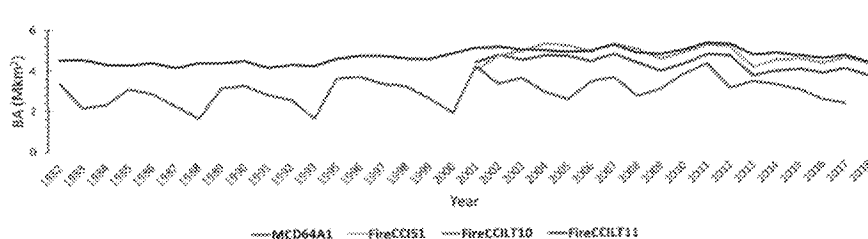
Note that Tu et al. (2024) report that the Power Dissipation Index (PDI), another different measure of the destructiveness of hurricanes that combines hurricane number, duration, and strength, has either remained unchanged or has declined in all global oceanic basins since the mid-1990s. As is clear, it is also not increasing and since 1990 has declined slightly.

Today's global climate simulations are too coarse to project changes in TCs directly. Rather, projections are derived from finer "downscaled" simulations or proxies involving sea surface temperatures, winds, and aerosols. By these methods, a warming climate is expected to show climate models project declining hurricane formation rates, in a warming climate (Chand et al. 2022). Climate models also project fewer Tropical Cyclones under future global warming, and even though models project they will increase in strength, the annual averages of rainfall maxima decline (Stensfield et al. 2020). Note that Tu et al. (2024) report that the Power Dissipation Index (PDI), a measure of the destructiveness of hurricanes, has either remained unchanged or has declined in all global oceanic basins since the mid-1990s.

### 8.7.22.272 Wildfires

The IPCC has not provided an assessment of wildfires.

As shown in Figures 8.7.3.479.1 and 8.3.5 global wildfire activity as measured by European Space Agency peaked over a decade ago and shows a downward trend since then in the 21<sup>st</sup> century.



**Commented [A9]:** I thought the trends were due to declining fires in the Amazon, masking any climate-related trend?

**Commented [A10R9]:** "global area burned appears to have overall declined over past decades, and there is increasing evidence that there is less fire in the global landscape today than centuries ago." Doerr and Santin, Proc Royal Society 2016

[ HYPERLINK  
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e-

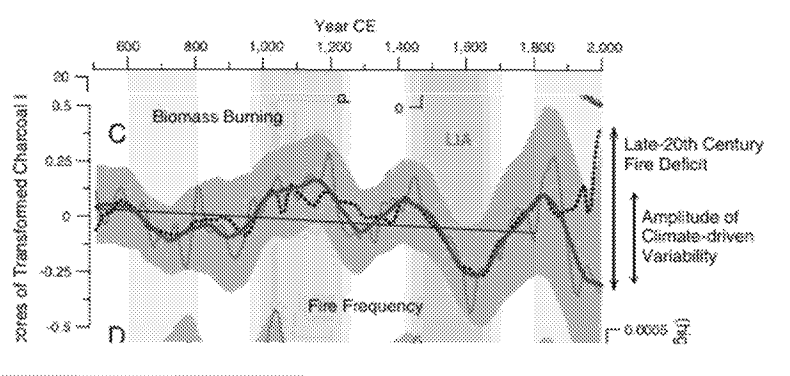
2017):%20https:\\web.archive.org\\web\\20200212033452\\https:\\www.nifc.gov\\fireInfo\\fireInfo\_stats\_totalFires.html" ]. 2018-2023: [ HYPERLINK "https://www.nifc.gov/fire-information/statistics/wildfires"]

Note that the NIFC has removed the pre-1960 data from its current website. They claim it is because measurement methods changed after 1960. This explanation seems inadequate since agencies blend temperature and extreme weather data series in other contexts when measurement systems changed. ~~in this case if anything,~~ The measurement of wildfires has improved since the early 20<sup>th</sup> century, so any bias will be towards understating early wildfire counts. Nonetheless just focusing on the post-1985 interval the number of fires is not increasing. The area burned did increase but only until about 2007.

Forest fires have always been a part of nature, and they can certainly create conditions that are inhospitable in the short term for all life including humans. Science has confirmed the overall benefit and necessity of the occurrence of forest fires. While recent high-profile fires and seasons serve as a reminder of the potential destructive impact, the highest profile forest fire remains the 1910 Big Blowup fire which destroyed over three million acres including the elimination of entire towns like Taft, MT (Apple 2020). The 1910 fire reshaped the U.S. Forest Service (National Forest Foundation 2022) leading to a focus on fire suppression with a primary goal to defeat all forest fires (Forest History Society 2022). This led to the 10 am rule in 1935 that meant all fires spotted on any day had to be controlled by the following day at 10 am (National Forest Foundation 2022).

While defeating fire is certainly a noble goal, questions began to arise as to whether this behavior "followed the science" (US Forest Service 2022). Over time the U.S. Forest Service has begun to rethink its behavior, recognizing that new approaches such as prescribed burns, fuel elimination and controlled wildfires are more appropriate (Sommer 2016). Recent research is validating this approach and recognizing that more frequent smaller fires in forests likely result in the most healthy forests, water ecosystems and biodiversity (Stephens et al. 2021).

It is difficult to establish a natural baseline for wildfire activity because of active fire suppression activity since 1900. Paleoclimatic evidence indicates, however, that past wildfire activity was much higher than at present. Marlon et al. (2012) used sedimentary charcoal layers to reconstruct fire history of western US for the past 1400 years. They also fit a model to predict expected fire activity as a function of climatic conditions. The results are summarized in Figure ~~8.7.2.2.3~~ below (from Figure 2 in their paper).

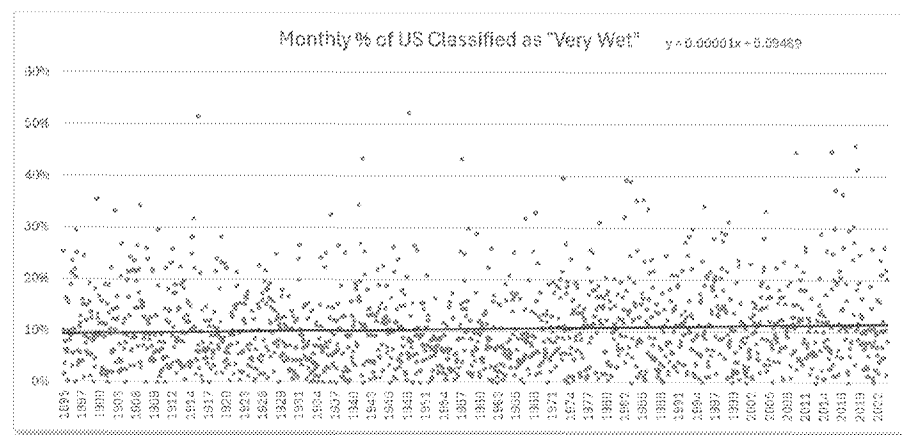


**Figure 8.2.37:** Fire frequency and fire deficit in the US. Source: Copied from Marlon et al. (2012)

In their figure the red line shows the smoothed charcoal record and the black dotted line shows the predicted charcoal record based on the statistical model. The gap at the end implies there has been a growing wildfire deficit over the 20<sup>th</sup> century. In other words, however much fire was observed in the 20<sup>th</sup> century it was less than what would have been observed in previous centuries based on the climatic conditions. Parks et al. (2025) likewise find that despite the recent increase in wildfire burn area in North America, a significant wildfire deficit remains relative to historical wildfire regimes there remains a significant wildfire deficit.

### 8.23.3 Precipitation

Figure 8.2.8 shows that US long term data from NOAA shows an insignificantly increasing tendency toward extreme wetness (+0.0001% per year)



**Figure 8.2.8:** Long term US wetness (%) Source: NOAA [HYPERLINK "<https://www.ncei.noaa.gov/access/monitoring/uspa/wet-dry/0>"]

Precipitation will be discussed further in the review of CONUS data below.

#### 8.23.4 Drought

As shown in Figure 8.3.9 US long-term data (NOAA) shows an insignificantly declining tendency toward extreme dryness (-0.001% per year)

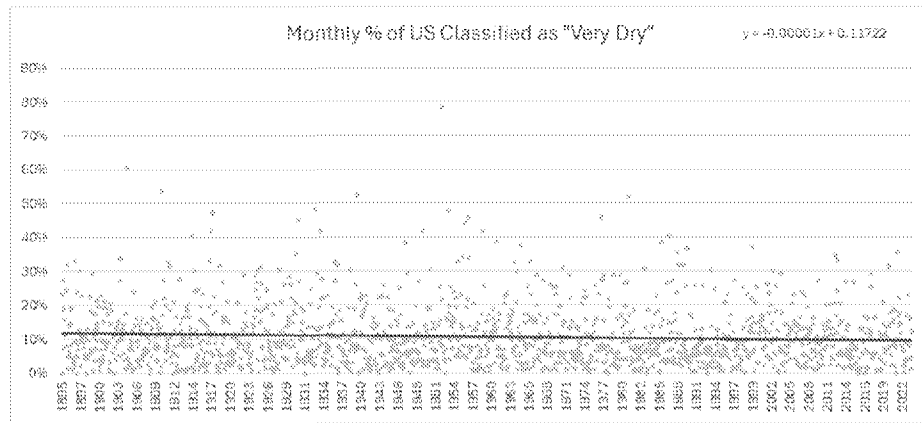


Figure 8.3.9: US dryness (%) 1895-2023. Source: NOAA [HYPERLINK "https://www.ncei.noaa.gov/access/monitoring/uspa/wet-dry/0"]

Kogan et al. (2020) examines a 30-year high-resolution satellite-based drought measure and concludes that global drought has not intensified and is not connected to climate change. "It is possible to state firmly that global and main grain countries' drought areas and intensity trends have not been following global climate warming since 1980's."

#### 8.3.4 Analysis of Temperature and precipitation extremes in the Conterminous Contiguous US (CONUS) data on temperature and precipitation extremes

##### 8.34.1 CONUS daily temperatures are becoming less extreme

Daily maximum temperatures in the warm season (TMax, May-Sep) and daily minimum temperatures in the cold season (TMin, Dec-Mar) are available beginning in Dec-1898 (126 years). (The dataset consists of 1,211 CONUS stations designated as United States Historical Climate Network or USHCN stations (Quinlan et al. 1987, Karl et al. 1990). These stations were selected by NOAA as having the fewest problematic issues with gaps, station moves and instrument changes. Where gaps still exist, nearby stations (bias-corrected) were merged so that the median volume of data available for a station is 98%. Although there are certainly errors certainly reside in the dataset, with over

**Commented [A11]:** Again, I think we need a map of where the stations are; something like this one:  
[HYPERLINK "https://www.researchgate.net/publication/258660497\_Uncertainties\_Trends\_and\_Hottest\_and\_Coldest\_Years\_of\_US\_Surface\_Air\_Temperature\_since\_1895\_An\_Update\_Based\_on\_the\_USHCN\_V2\_TOB\_Data/figures?to=1"]  
More importantly, it needs to show how you've cut them up into regions

1,000 stations we can have relatively high confidence in any underlying signal we that might be discovered, can be characterized by relatively high confidence.

We begin with the question of whether the occurrence of daily record high or low temperatures changed has changed since Dec 1898. Each warm season has 153 days (1 May to 30 Sep) and each cold season has 123 days (1 Dec to 31 Mar). For each station and day we calculated the year in which the record highest (lowest) temperature occurred. With 126 years of observations, if there were no temperature trends over time, the expected number of records for TMax would be 1.21 ( $=153/126$ ) per station per year and for TMin 0.96 ( $=123/126$ ) per station per year. Figure 8.4.14 indicates the observed distribution in time of the occurrence of these extreme events.



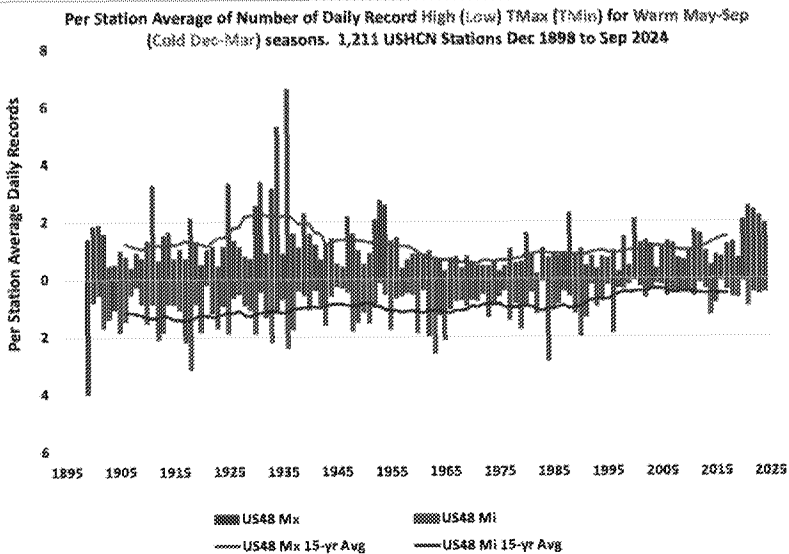
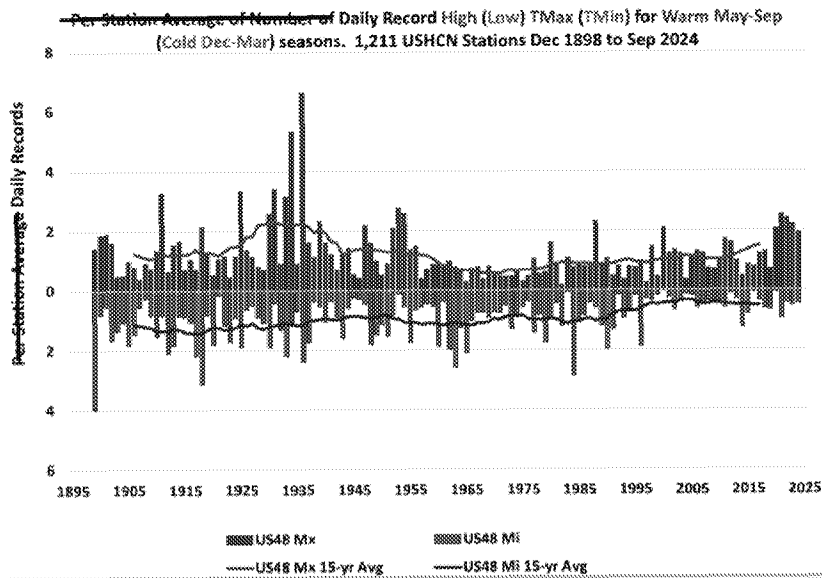


Figure 8.1.110 Number of daily record High (red) and Low (blue) for warm and cold seasons in the CONUS. The lines represent the 15-year running, centered average. Source: 1,211 USHCN stations supplemented as needed to achieve a minimum of 92% of observations in the 126-year period since Dec 1898.

The results indicate a common feature in many metrics of warm-season extremes in the CONUS—the exceptional heat of the 1920s and especially the 1930s, peaking in 1936. On a per-station average, 60% of the TMax records and 59% of the TMin records occurred in the first half of the period (1899–1961).

On the cold side, the Valentine's Day Arctic outbreak in Feb. 1899 stands as the most extensive cold extreme experienced by the CONUS, with 1917–24. The frequency of cold records has declined, especially over the last quarter of the period in which only 13% of the extreme cold events were measured. In contrast, 35% of the extreme TMax records were achieved in the last quarter in accordance with statistical expectations. These general features have been noted in past assessments (IPCC AR5, IPCC AR6, NCA4, NCA5). Combining the two records the overall reduction in numbers of both cold and hot extremes over the past century indicates a climate less prone to extremes.

This pattern is also shown in Figure 8.4.2.1.1. For each station and for each year the hottest warm season and coldest cold season temperatures were calculated and converted to anomalies relative to the station's long-term warm and cold season (respectively) averages. Then the differences between these were computed by station and geographically averaged over all stations, thus yielding an annual measure of the expected range of local extreme temperatures for each year. Figure 8.1.1 shows the 15-year trailing average of this measure which has clearly declined over the past century.

**Commented [A12]:** Does this include a correction for varying station density? If not, it should just read "averaged".

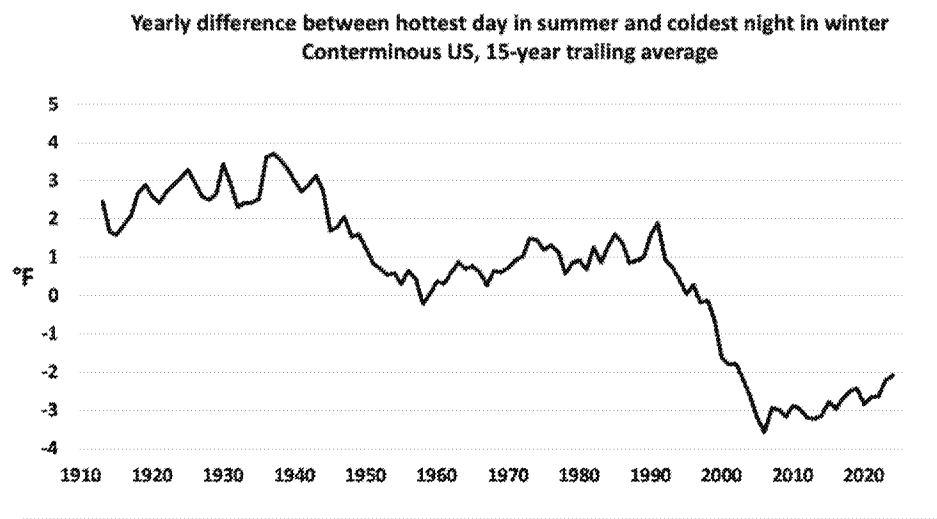


Figure 8.4.2.1.1—15-year trailing average of the difference each year of each station's hottest warm season TMax and coldest cold season TMin relative to the long-term average.

The average difference for each station between the hottest summer TMax and coldest winter TMin has declined about 5°F in the past 126 years. The decline is due mostly to warming winter TMin, but

a decline in the magnitude of summer TMax is also a factor. The rise in TMin has been strongly related to the growing presence of manufactured surfaces around the weather stations over the last 100+ years (Spencer et al. 2025).

Summarizing Figures 8.10.4.1 and 8.4.2.1, while temperature extremes are regularly experienced in the US and attract a great deal of media attention, long-term records show the US climate has become less extreme over time (milder), when measured in terms of the range between warm season maxima and cold season minima.

#### 8.34.2 Exceedances of a heat threshold

Under the heading of "The Risk of Temperature Extremes is Changing", the most recent US National Climate Assessment report (NCA5) notes the increase in a threshold metric of number of days at or above 95°F, stating:

*"The western US has been particularly affected by extreme heat since the 1990s, experiencing a larger increase in days over 95°F, as would be expected given the greater warming in that region relative to the eastern US. Several major heatwaves have affected the US since 2018, including a record-shattering event in the Pacific Northwest in 2021."*

Are the occurrences of 95°F days changing? In a climate as varied as that of CONUS, threshold statistics can be misleading. A region with many stations which ~~that~~ have near 95°F TMax average temperatures in the summer might see large swings in the metric when only small changes in average temperatures occur. Elsewhere with stations that either rarely or virtually always achieve 95°F TMax temperatures, a small change will not impact the results much at all. In the past 126 years, the average CONUS station experienced 129 days exceeding 95°C per 6-yr period, but the regional values range from 278 in the Southern Plains to 9 in the Northeast. Thus, one needs to view such threshold analyses with caution.

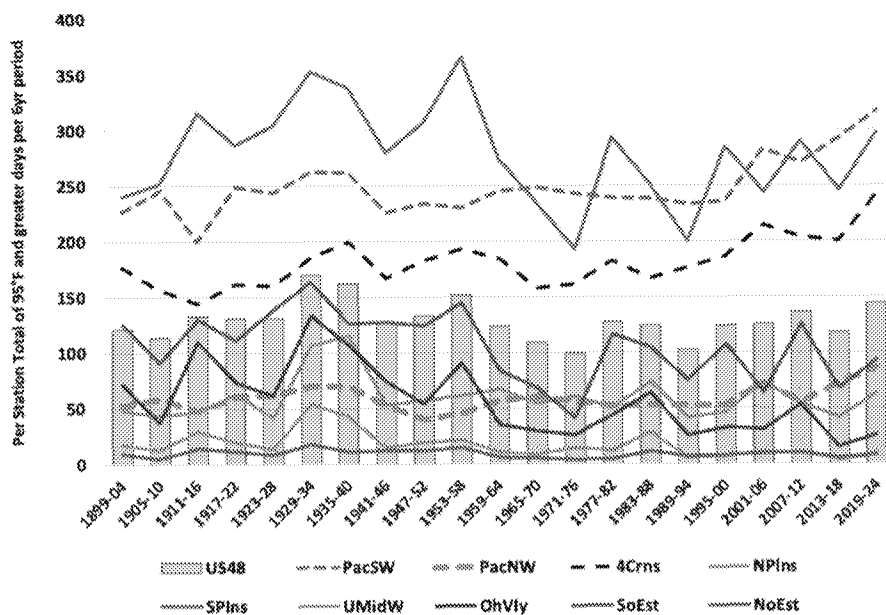


Figure 8.12.4.3. Total number of days  $\geq 95^{\circ}\text{F}$  in 6-yr periods, US 48 (bars) and regions (lines).

In Fig. 8.12.4.3, we see that only three of the nine regions, all in the West, have experienced upward trends in the number of  $95^{\circ}\text{F}$  or hotter days (dashed lines). The CONUS as a whole has not and the other six regions have experienced declines.

The Pacific NW heatwave of 2021 is referenced as supportive information for of the NCA5 claim: an event we examined more closely in Section 6.4. The evidence indicates it was a “black swan” event, i.e., a single, unprecedented event in the existing record, not part of a suggesting it is not indicative of a pattern of increasing extreme heat. For example, the 5-day average tropospheric grid-point temperature anomaly over the Pacific NW during that event was  $+10.8^{\circ}\text{C}$ , the most extreme NH grid-point summer anomaly in the 46 years from over 4 million grids. In contrast, the global anomaly during that time was virtually zero ( $+0.03^{\circ}\text{C}$ , Mads et al. 2024).

The heading “The Risk of Temperature Extremes is Changing” suggests positive trends are now being observed in threshold temperatures on a widespread basis, but that is not evidenced in the combined CONUS results of the figures above.

### 8.3.4.3 Heatwaves

Heatwaves (consecutive days that exceed an extreme threshold) have a greater societal impact than Of more impact than a single daily record. We measure is the phenomena of heatwaves, or consecutive days which exceed an extreme threshold. For this study, the metric will be the number of “Heatwave Days” here defined as the sum count of all days in May-Sep each year which that exceed

the 90<sup>th</sup> percentile and that occur lie within consecutive periods a run of at least six consecutive days in length. This is equivalent to the method used in NCA5 except that the reference period here is the entire record 1899-2024 while NCA5 limited truncated the reference period to 1961-1990, a cool episode finale. By selecting 1961-1990, the final truncation occurrence of heat positive results (days exceeding the 90<sup>th</sup> percentile) will be enhanced in periods warmer than the reference base period, especially if starting in 1960 and moving to the present (see *Urban Influences* below).

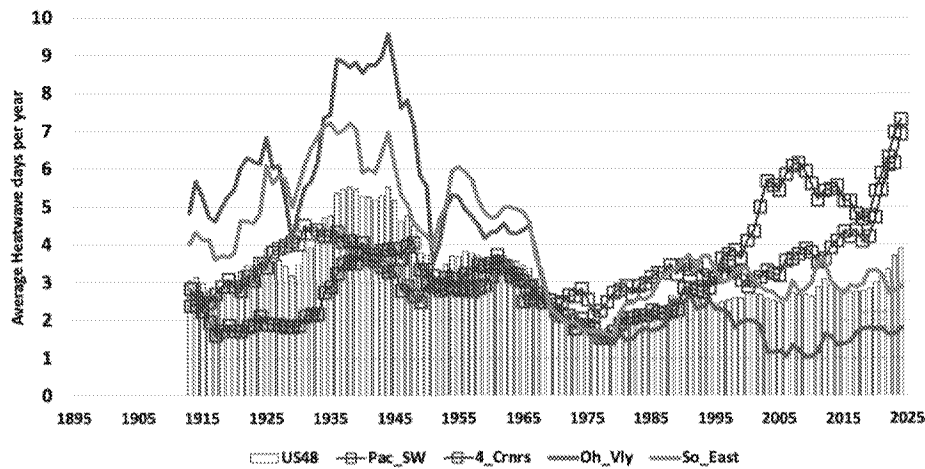


Figure 8.13 4-15-year trailing average of number of heatwave days per year per station in the CONUS (bare) and four regions: Pac\_SW (purple squares, CA, NV), 4\_Cnrs (red squares, AZ, NM, UT, CO), Oh\_Vly (blue, MO, IL, KY, TN, IN, OH, WV) and So\_East (green, MS, AL, GA, FL, SC, NC, VA).

Figure 8.13.4.4 indicates again the excessive heat of the first half of the 20<sup>th</sup> century, primarily in the eastern two-thirds of the nation, as seen in the regional values for the Ohio Valley and the Southeast as examples. The West has seen a recent increase of heatwave days and the two regions with the highest number are shown, the Pacific Southwest and the Four Corners (NCA5). This indicates that the background warm season circulation favored heatwaves in the eastern portions of the country in the first half of the 20<sup>th</sup> century, but in the 21<sup>st</sup> century the patterns have favored heatwaves in the West. For CONUS as a whole, heatwaves are no more common today than they were a century ago.

Of interest here is the regional variation of this metric. The four northern regions (Pacific NW, Northern Plains, Upper Midwest, and Northeast) on average experience 15 to 27 heatwave days per 15-year period. In contrast, the five southern regions (Pacific Southwest, 4-Corners, Southern Plains, Ohio Valley and Southeast) see 37 to 54 such days, essentially twice as many. This suggests the summer circulation pattern is more prone to stationary events in the southern regions while transient systems in the northern regions are more common and thus cut short these potentially longer events.

#### Urban influences

The NCA5 directs readers to the website [HYPERLINK "https://www.globalchange.gov/indicators/heat-waves"] (USGCRP 2023) to view the number of urban heatwaves by decade from the 1960s. The figure reveals shows a monotonic increase in each decade from 2 occurrences per year in the 1960s to 6 in the 2020s. The definition of a heatwave is an unusual but practical measure from a human discomfort perspective—a period of at least 2 consecutive days when the minimum apparent minimum temperature (combination of temperature and humidity) exceeds the 85<sup>th</sup> percentile. Note too, the dataset is limited to the 50 largest U.S. cities in the US.

These increasing values since 1960 presented in USGCRP (2023) are entirely reasonable, but are unrelated to GHG emissions for at least two reasons unrelated to GHG emissions. Urbanization in these cities is a major factor in the rise of TMin relative to co-located TMax and relative to TMin at rural stations. Also, the 1960s was the coldest decade and 1970s the second coldest decade since the 1910's, so this starting date preconditions the time series to show increases. This does not dismiss the real rise in nighttime temperatures in major U.S. cities and the societal impacts associated with these changes. However, we note for a variety of reasons, that summer TMax (especially in rural areas) serves as better response variable for detecting potential changes in heatwaves influenced by changes in the background climate due, for example, to increasing GHGs (Christy et al. 2009). For the CONUS as a whole, the evidence in this section suggests GHG emissions have had little to no effect on heatwaves in the CONUS.

#### 8.3.4.4 Extremes in daily precipitation.

Because precipitation involves a discrete phase change (water vapor to liquid), it is due to its stochastic and episodic in character and therefore precipitation requires careful statistical treatment to understand variability over long time periods (see 8.1 Introduction). The US National Climate Assessments (NCA4, NCA5) have highlighted an increase in the occurrence of the heaviest precipitation events (defined in different ways) primarily in the eastern half of the CONUS, especially the Northeast, when starting in either 1901 or 1958. Interestingly, the regional variations indicate that the largest increases in extreme events are in the Northeast and least the smallest in the West, which is a trend counter to the changes in temperature extremes shown above.

Commented [A13]: Stochasticity and LTP are really different things, but we somehow conflate them in this sentence. Or am I missing something?

Commented [A14R13]: By removing the 'therefore' I think we are now not conflating them.

McKrick and Christy (2019) examined long-term and consistent station observations of daily precipitation to test some of these NCA claims for the Southeast and West Coast. In neither case when the time series were extended back in time (as far as 1872 in some cases) or when starting later (1978), there were no were the trends significant trends for either region. For this report we updated these findings with similarly constructed observations from 20 stations on the Pacific Coast (1938 from San Diego, CA to Blaine, WA, see Figure 8.14), 24 stations in the humid Southeast (1972 from Austin, TX to Washington, DC, see Figure 8.15), and 21 stations in the Northeast (1888 from Buffalo, NY to Gardiner, ME, see Figure 8.16). The results were as follows:

##### Pacific region:

- .....Average precipitation trend is significant (downwards) in Astoria, insignificant elsewhere.
- .....The trend in rainfall variance is positive and significant in Big Sur, insignificant elsewhere.
- .....The trend in daily maximum precipitation is positive and significant in Aberdeen and Big Sur and negative and significant in Newport (insignificant elsewhere).
- .....Averaged over all stations in the region none of these three trend parameters is statistically significant.

##### Southeast region:

- The trend in average precipitation is positive and significant in Mobile and Quito, insignificant elsewhere.
- The trend in rainfall variance is positive and significant in Mobile, insignificant elsewhere.
- The trend in daily maximum precipitation is positive and significant in Vicksburg and Norfolk, insignificant elsewhere.
- Averaged over all stations in the region none of these three trend parameters is statistically significant.

#### Northeast region:

- The trend in average precipitation is positive and significant in 9 of 21 locations and in the region averaged overall.
- The trend in rainfall variance is positive and significant in Portland, Albany and Buffalo, insignificant elsewhere.
- The trend in daily maximum precipitation is positive and significant in Portland and Gardiner, insignificant elsewhere.
- Averaged over all stations in the region the trend parameters for variance and maximum precipitation are not statistically significant.

In the Pacific region, over the whole sample, the trend in average precipitation trends downward, being significant only in negative and significant in Astoria, and insignificant elsewhere. The trend in rainfall variance increases, is positive and significant only in Big Sur, and insignificant elsewhere. The trend in daily maximum precipitation is positive and significant in Aberdeen and Big Sur and negative and significant in Newport and insignificant elsewhere. Averaged over all stations in the region none of these three trend parameters is statistically significant.

In the Southeast region over the whole sample the trend in average precipitation is positive and significant only in Mobile and Quito, the trend in rainfall variance is positive and significant only in Mobile and the trend in daily maximum precipitation is positive and significant only in Vicksburg and Norfolk. Averaged over all stations in the region none of these three trend parameters is statistically significant.

The Northeast region exhibits a pattern of increasing average rainfall. The trend in average precipitation is positive and significant in 9 of 21 locations and in the region averaged overall. The trend in rainfall variance is positive and significant only in Portland, Albany and Buffalo and insignificant elsewhere and not in the regional average. The trend in daily maximum precipitation is positive and significant only in Portland ME and Gardiner ME and insignificant elsewhere and not in the regional average.

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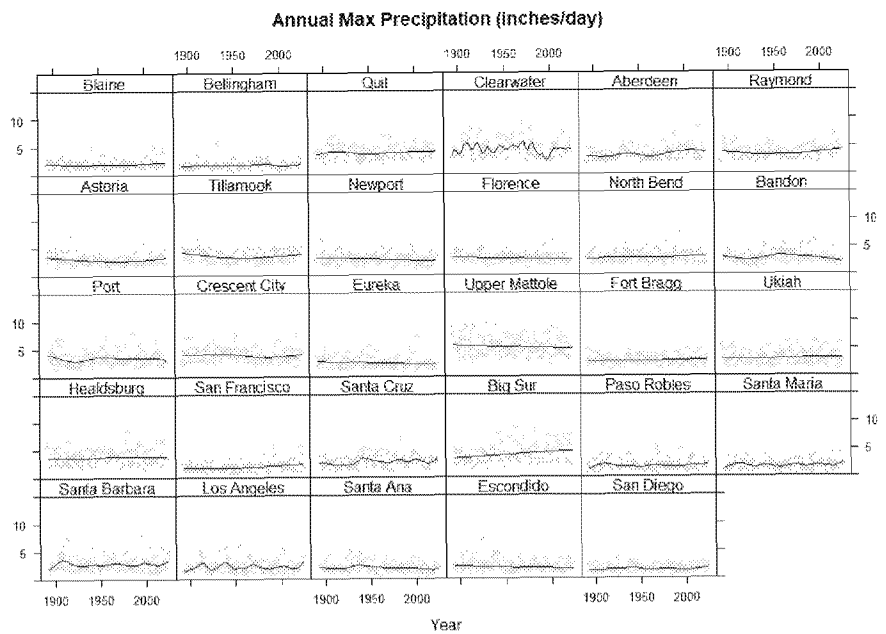


Figure 9.1.1 Annual maximum precipitation for 25 Pacific stations 1950 to present



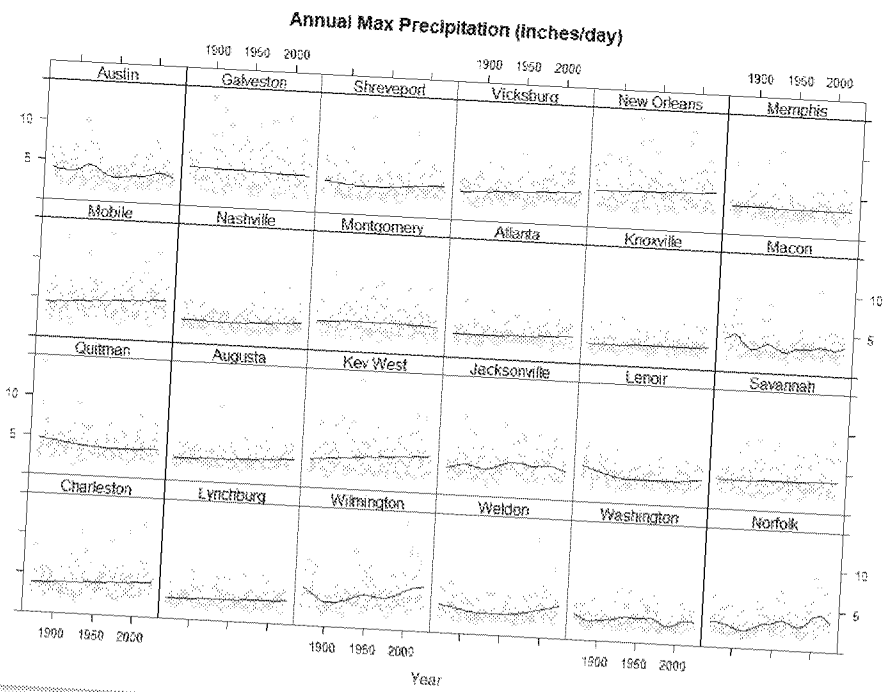


Figure 8.12 Annual maximum precipitation for 24 Southeast stations 1972 to present

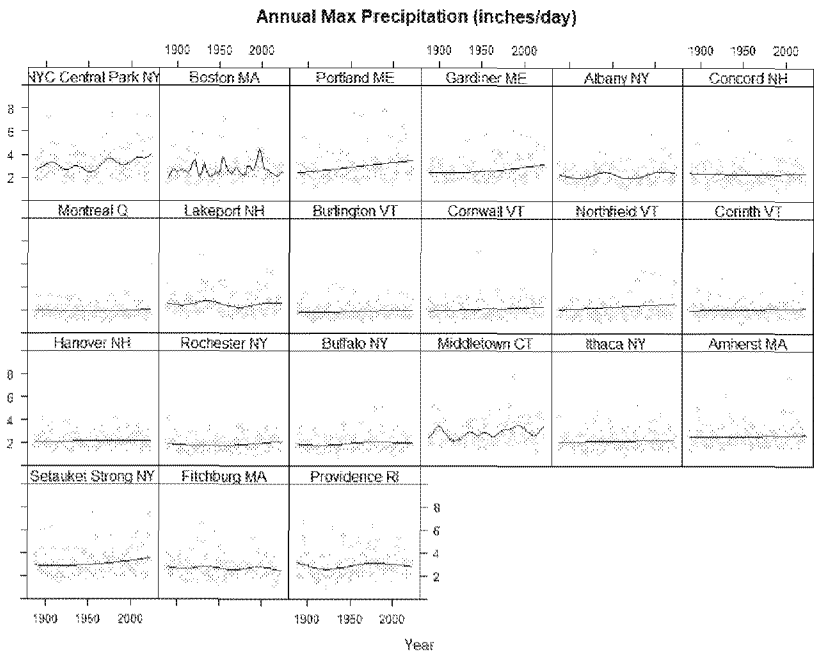


Figure 8.13 Annual maximum precipitation for 21 Northeast stations 1898 to present

#### Pacific Coast heavy rainfall events

The Pacific Coast receives considerable amounts of precipitation from Atmospheric River (AR) events which often last more than a day or two (e.g., Gershunov et al. 2017, Pan et al. 2024). The worst known such event in recent history was the ArkStorm that occurred between December 1861 and January 1862, which dumped nearly 10 feet of rain in parts of California and submerged the entire Central Valley for weeks under as much as 15 feet of water (Brewer 1930, Nall and Halbert 2007). Paleoclimate research has found six megastorms more severe than 1861–1862 in California during the last 1000 years, occurring at intervals of 300 years or so (Porter et al. 2011).

#### SIDEBAR: Perils of short data records

San Francisco provides a good case study of the limitation of using short historical samples to characterize natural variability of extreme events. Suppose we use a 130-year sample of daily San Francisco precipitation from 1895 to 2024 and we look for 3-day, 5-day, 14-day and 30-day rainfall records. The results are as shown in Table 8.12.

| Event  | Record (inches) | Year |
|--------|-----------------|------|
| 3-day  | 6.94            | 2023 |
| 5-day  | 6.55            | 2023 |
| 14-day | 12.62           | 2023 |

30-day 1893 1998  
Table 8.12: Extreme rainfall records, San Francisco, 1893-2024.

The records all cluster in the more recent data. 2023 appears to be an exceptional year and since it is near the end of the sample it would might point to the possibility suggest that the climate has shifted into a potentially more hazardous state, perhaps as a result of human influences.

But the picture is very different if we use a sample that begins 115 years earlier, in 1850. If we extend the record back to 1850 the picture changes. Table 8.2.3 shows that the record-setting events then all happened in the 1860s. Furthermore 2023 is now not even in 2<sup>nd</sup> place but falls to 3<sup>rd</sup> or 4<sup>th</sup>. Also, comparing the records of the two charts the extreme precipitation events in 1862 and 1867 involved considerably more rainfall than the 1995 and 2023 events, with 14- and 30-day totals about 50 percent higher.

Commented [A16]: Check this

| Event  | Record (inches) | Year | Rank of 130-yr extreme |
|--------|-----------------|------|------------------------|
| 3-day  | 8.85            | 1867 | 3                      |
| 5-day  | 9.80            | 1867 | 3                      |
| 14-day | 19.05           | 1862 | 4                      |
| 30-day | 28.25           | 1862 | 2                      |

Table 8.23: Extreme rainfall records, San Francisco, 1850-2024.

The The characterization of the range of natural variability is made even more remarkable when paleoclimate evidence is examined. Porter et al. (2011) discovered that in the past 1,800 years at least six megastorms were more intense than the devastating 1861-62 Arktstorm that struck the region. Thus, evidently, such extreme events have impacted the region about every 300 years, though not since 1895.

This example illustrates the limitations of using relatively short climate periods (~130 years) to assess the character and range of natural variability in general and of extreme events in particular. Accurate representation of the full range of natural variability is necessary for any attribution analyses (see 6.4). Infrastructure planners, emergency management institutions and attribution scientists would understand the significant mischaracterization of the magnitude of a future extreme if based only on the last 130 years. In this case, a single time sample of 130 years provides an underestimation of the extreme value by up to 50% determined when adding only 45 more years of observations. Compared to millennial-scale paleoclimate evidence, an even greater underestimation would occur. An important lesson is that the climate can deliver great surprises on its own even without human influences.

We examine occurrences of 5-day deluges as follows. In a 130-year span there are 26 5-year intervals. At each location we computed the 5-day precipitation totals throughout the year and selected the 26 highest values. A single year may have more than one of the 26 heaviest. Each of these can be thought of as 1-in-5-yr events. If there are no trends in precipitation then the total number of these events across all stations should be evenly spread out on an annual basis over the years. In Fig. 8.14.4.5 we show the distribution in time of these events. The deluges associated with the massive 1997-98 El Niño event are readily apparent. While erratic, as is typical of these types of precipitation metrics, there is no indication of a tendency to become more frequent over time.

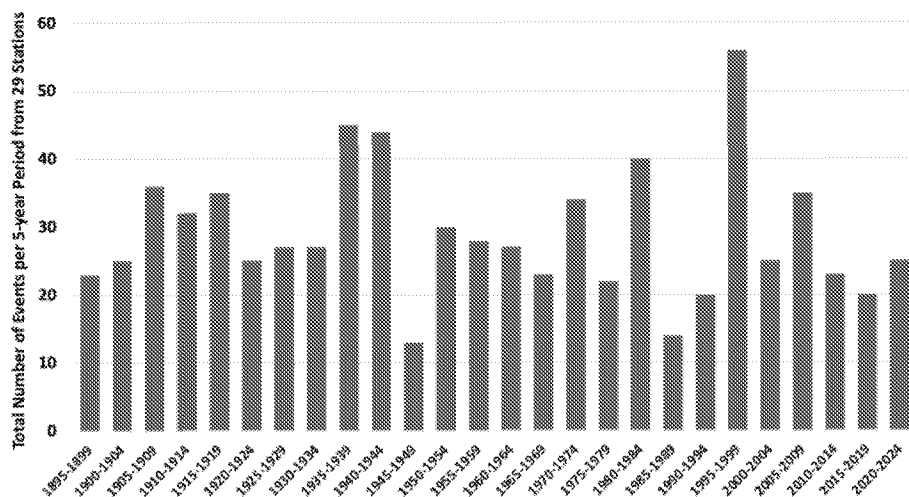


Figure 8.144.5 The time distribution by 5-year periods of the 26 heaviest occurrences for each station (i.e., nominal 1-in-5-year event).

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#### Southeast heavy rainfall events

The temporal pattern of 5-day totals of the 1-in-5-yr heavy events in the humid Southeast (Figure 8.151.6) is generally unremarkable, though a cluster of higher values appears in 1995 to 2019. The increase in those years is due largely to the 4 northeastern-most stations of Wilmington NC, Weldon NC, Washington DC, and Norfolk VA. This confirms the pattern indicated in NCA4 and NCA5 of a tendency for an increasing frequency of heavy events, due to a temporal clustering of tropical storms from eastern NC to Maine discussed below. Otherwise, the remaining 26 stations show an unremarkable temporal distribution of heavy events.

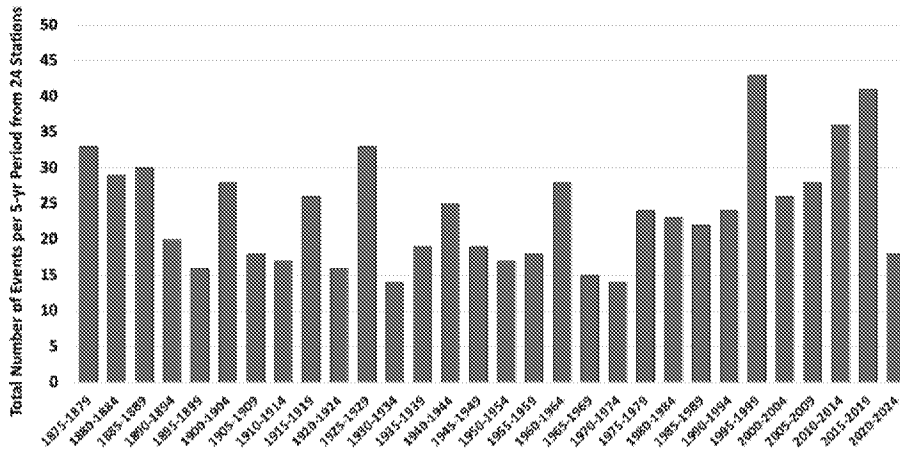


Figure 8.154.6. As above but for the 30 heaviest 1-in-5-yr events for 24 stations in the humid Southeast from Austin, TX to Washington, DC in 5-year bins for 1875-2024.

#### Northwest heavy rainfall events

Fig. 8.16.4.2 shows the 27 (1-in-5-yr) heaviest 3-day events for the last 135 years in 21 stations in the Northeast (including Montreal, Canada). We use 3-day totals here as this produced the largest variations in time. In this region, 72% of the events occur during June to October and are dominated by tropical incursions of hurricanes, tropical storms or tropical storms that transition to extratropical systems. According to NCA4 and NCA5 this region experienced the largest increases in extreme events, so it shall be examined more closely.

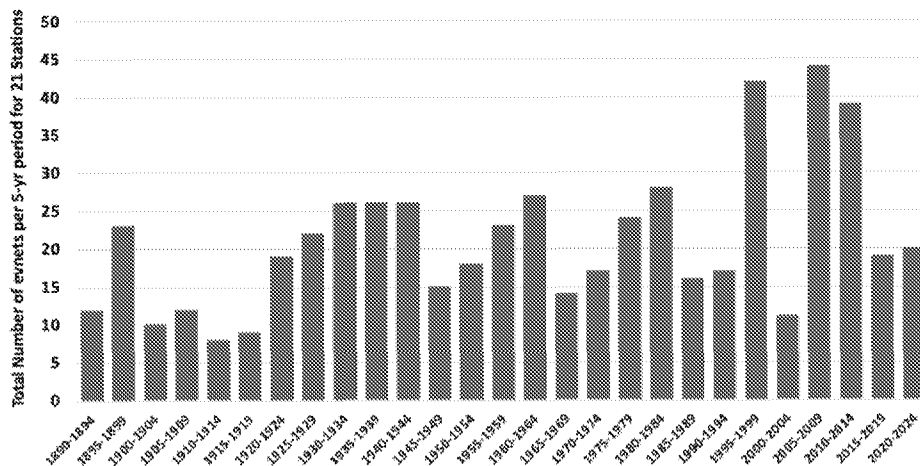


Figure 8.16.4.7. Time distribution of the heaviest 27 (1-in-5-yr) heaviest 3-day precipitation events for 21 stations from NY to ME, including Montreal.

Howarth et al. (2019) report differences in the Northeast between two 18-year periods: 1979-96 and 1997-2014 (a similar region as in Fig. 8.16 that includes PA and NJ) of various precipitation extremes. One metric which indicated a dramatic increase (317%) was found for 24-hr events  $\geq 6$  inches. This high increase is due to the very small numbers of such events of which there were only 6 in the first period and 25 in the second as reported for 58 stations. This high percentage increase is due to the very small numbers of the events; only 6 in the first period and 25 in the second. Most of the stations did not record such an event suggesting these erratic, episodic events over brief 18-yr periods, need scrutiny by additional statistical methods.

Using the information in Fig. 8.16.4.7 over the same years as Howarth et al. we find a 51% increase in the frequency of heavy events between the two periods. One can see in Fig. 8.16 that it was unfortunate that Howarth et al. ended in 2014 prior to a return to the long-term average of such events.

A feature of Howarth et al. is the use of single-day totals which is questionable because extreme events are often spread across the time-of-observation boundary. Thus stations measuring at 0700 LT versus those at Midnight will have differing results for a particular event which would then have major impacts on counting these events. We use the 3-day totals in Fig. 8.16.4.7 to be sure to capture the extent of these extreme downpours. In any case, we can confirm that the period 1997 to 2014 experienced a cluster of heavier events as Howarth et al. have documented.

Howarth's most remarkable claim (317% increase in 6" days) is potentially misleading because it is a threshold statistic (see Section 8.3.4.2 above) and a ratio of small numbers over a short period. The result is not representative of relative extreme events for the whole region since the majority of stations never experienced a 6" total. Fig. 8.16 above determines the same number of events for each station (27 heaviest events) whose heaviest values ranged from 4.4" to 12.5" and their 27<sup>th</sup> heaviest values ranged from 3.3" to 5.0". This analysis thus allows each station to be equally represented. In

other words, if there is a region-wide increase in heavy events, it should be seen in the sum of all stations. Note too that the period of record here is 135 years vs. 36 years of Howarth et al. Except for three 5-year periods between 1995 and 2014 there is nothing statistically remarkable about the results in Fig. 8.164.2.

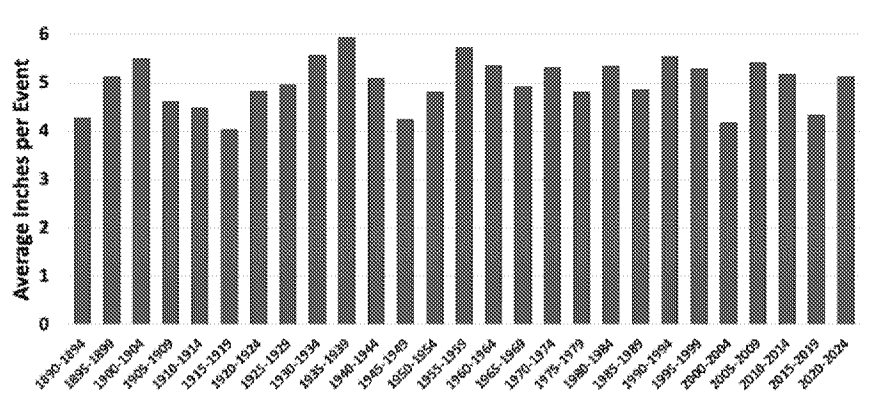


Figure 8.174.8. Average amount of precipitation falling in the 1-in-5yr events for the NE stations.

An interesting aspect of Northeast precipitation is that there has been no change in the amount of precipitation per heaviest event, as shown in Fig. 8.174.8. The trend is only  $+0.02$ /decade. The highest amount, 1935-39, includes the Great New England Hurricane of 1938, one of the rare major (Category 3 or higher) hurricanes to strike the region. The results in Figs. 8.164.5 and 8.164.7 suggest that though there was an uptick in the number of events during the period 1995 to 2014, the events, individually, are not becoming more intense.

Jong et al. (2024) document the increase of tropical influences on precipitation events in the Northeast since 1959 and concluded, "The autumn extreme precipitation trend over the Northeast US is primarily attributed to tropical cyclone-related events since the 1990s." The question then becomes, was the temporal clustering of tropical systems in 1997-2014 which affected the Northeast a response to increasing GHGs? Jong et al. examined CMIP-6 model output which suggests that there will be fewer such systems in the 21<sup>st</sup> century but that the intensity of the rainfall events might increase. This conjecture is not seen in Fig. 8.17 where the amount per event has remained steady over the 135-year period.

For substantial urban areas there is some evidence to indicate the heaviest rainfall events may be redistributed due to the impact urban infrastructure has on the local weather (e.g., Pielke Sr. et al. 2011; Zhang et al. 2018; Yang et al. 2024). Yang et al. state, "Cities that experience compact development tend to witness larger increases in extreme rainfall frequency over downtown than their rural surroundings, while the anomalies in extreme rainfall frequency diminish for cities with

dispersed development." While this is an important insight to consider, the effect on the specific stations used in this analysis is unknown, or at least not detectable in Fig. 8.1.7.

In summary, the evidence from the historical record of extreme precipitation events in the CONUS is generally not consistent from region to region so that inferences regarding trends and their projections are wrought with significant uncertainty. In most regions and perhaps all, it is our opinion that the very nature of the erratic and episodic character of extreme precipitation events renders the discovery of statistically significant changes, including a relationship to CO<sub>2</sub> concentrations, a recultyst to be achieved (McKerriek and Christy 2019).

#### 8.7.4.5.10 Summary

To be inserted

Based on the content provided in the document, here are the five most important takeaways:

- Limited Detection of Anthropogenic Signals: The IPCC has asserted high confidence in detecting an anthropogenic signal in only 1 out of 34 weather impact categories, and medium confidence in 4 more. For the remaining 26 categories, no anthropogenic signal is claimed to be detected.
- Slow Emergence of Trends: Even under the most extreme forcing scenario (RCP8.5), the IPCC expects very few anthropogenic trends to emerge within this century for most weather impacts.
- Natural Variability Dominance: Natural variability continues to dominate patterns of extreme weather systems. Simple assertions of trend detection are often complicated by regional heterogeneity and trend reversals over time.
- RCP8.5 Scenario Implausibility: The document notes that the RCP8.5 scenario is described as an implausible high-end storyline, not a "base case" or "business-as-usual" projection.
- Conflicting Messages on Attribution: The document mentions that AR6 (IPCC Sixth Assessment Report) offers conflicting messages about the attribution of extreme weather to anthropogenic causes, highlighting the complexity and uncertainty in this area of climate science.

These takeaways emphasize the nuanced and complex nature of attributing extreme weather events to climate change, and the importance of considering natural variability and uncertainty in climate projections.

**Commented [A18]:** Out of curiosity (and perhaps utility), I fed the entire document (absent this section) into Anthropic's Claude-3.5-sonnet LLM and asked it what are the five most important takeaways. This is what it produced. I'd judge it not a bad start that will need some human improvement, which I'll undertake on the next iteration.

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## Appendix: Review of IPCC and NCA Findings on Extreme Weather

The sources we review will be denoted as follows:

**SREX:** The IPCC *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (2012)

**AR5:** The IPCC *Fifth Assessment Report Working Group I* (2013).

**AR6:** The IPCC *Sixth Assessment Report Working Group I* (2021).

**NCA17:** The *US Climate Science Special Report of the Fourth National Climate Assessment* (2017) Volume I Chapter 6.

### 8A.1 Overview: IPCC Assessment of signal emergence in extreme weather types (AR6 WG1 Table 12.12)

Table 8A.1 reproduces the findings of AR6 Table 12.12 which indicates, for 34 major weather event and impact types, whether a signal of anthropogenic forcing has been detected in the historical record (column 1), whether such a signal is likely to emerge by 2050 under the extreme RCP8.5 scenario (column 2) and whether it is likely to emerge by 2100 under RCP8.5 forcing (column 3). It should be borne in mind that the latter two columns suffer from the deficiencies of GCMs discussed in Chapter IX. And as we discussed in Ch. X on attribution, AR6 offers three conflicting messages within the AR6 regarding about attribution of extreme weather. Nevertheless, we provide this Table is provided here for reference.

Several patterns stand out. First, detection of an anthropogenic signal is asserted with *high confidence* in only four out of the 34 weather impact categories an anthropogenic signal is asserted with *high confidence* in only four, and with *medium confidence* in a further four. For the rest, the IPCC does not NOT claim to have detected an anthropogenic signal in the remaining 26 categories. Of the four *high confidence* assertions, two are for changes in average temperatures (air and ocean), which hence are not measures of extreme weather. Also two further, two of the four *medium confidence* assertions are related to ocean chemistry and thus are likewise not related to extreme weather. The IPCC does not NOT assert a detectable human influence on many non-temperature weather features such as wind, precipitation, flooding, and drought, etc.

Second, as shown in columns 2 and 3 show that the IPCC expects very few such anthropogenic trends/signals to emerge within this century, even under the most extreme forcing scenario. As we discuss in Section 4.2 the RCP8.5 scenario is an implausible high-end storyline, it is not a “base case” or “business-as-usual” projection. Yet even still, even so, most weather impacts are not expected to exhibit show an anthropogenic signal this century. As will be clear from the underlying report text, natural variability dominates patterns of extreme weather systems and simplistic assertions of trend detection are frequently undermined by regional heterogeneity and trends reversals over time.

| Climate Impact Driver Type | Climate Impact Driver Category | Already emerged in the Historical Record <sup>1</sup> | Emerging by 2050 in Most Extreme CO <sub>2</sub> Emission Scenario <sup>2</sup> | Emerging by 2100 in Most Extreme CO <sub>2</sub> Emission Scenario <sup>2</sup> |
|----------------------------|--------------------------------|-------------------------------------------------------|---------------------------------------------------------------------------------|---------------------------------------------------------------------------------|
| Heat & Cold                | Average air temperature        | YES in most regions                                   | YES                                                                             | YES                                                                             |
|                            | More heat extremes             | YES in most regions                                   | YES in land regions                                                             | YES                                                                             |
|                            | Fewer cold extremes            | YES in a few regions                                  | YES in many regions                                                             | YES                                                                             |
|                            | Less frost                     | NO                                                    | NO                                                                              | NO                                                                              |

|              |                                         |                          |                       |                       |
|--------------|-----------------------------------------|--------------------------|-----------------------|-----------------------|
| Water & Dry  | Average precipitation (inches per year) | NO                       | YES (less) YES (decr) | YES (less) YES (decr) |
|              | River flooding                          | NO                       | NO                    | NO                    |
|              | Heavy precipitation & drought periods   | NO                       | NO                    | YES in a few regions  |
|              | Landslides                              | NO                       | NO                    | NO                    |
|              | Fertility                               | NO                       | NO                    | NO                    |
|              | Hydroelectricity                        | NO                       | NO                    | NO                    |
|              | Agricultural & residential drought      | NO                       | NO                    | NO                    |
| Wind         | Fire weather                            | NO                       | NO                    | NO                    |
|              | Average wind speed                      | NO                       | NO                    | NO                    |
|              | Severe wind storms                      | NO                       | NO                    | NO                    |
|              | Tropical cyclone                        | NO                       | NO                    | NO                    |
| Snow and Ice | Snow and dust storms                    | NO                       | NO                    | NO                    |
|              | Snow, glaciers & ice sheets             | NO                       | YES in a few regions  | YES Arctic snow       |
|              | Permafrost                              | YES                      | YES                   | YES                   |
|              | Lake & river ice                        | NO                       | YES                   | YES                   |
|              | Arctic sea ice                          | YES                      | YES                   | YES                   |
|              | Antarctic sea ice                       | NO                       | YES                   | YES                   |
|              | Heavy snowfall and ice storms           | NO                       | NO                    | NO                    |
|              | Hail                                    | NO                       | NO                    | NO                    |
|              | Snowmelt rate                           | NO                       | NO                    | NO                    |
|              | Snowmelt level                          | NO                       | YES                   | YES                   |
| Coastal      | Coastal flood                           | NO                       | NO                    | NO                    |
|              | Coastal erosion                         | NO                       | NO                    | NO                    |
|              | Coastal upland erosion                  | NO                       | NO                    | NO                    |
| Open Ocean   | Average ocean temperature               | YES                      | YES                   | YES                   |
|              | Marine biodiversity                     | NO                       | NO                    | NO                    |
|              | Ocean acidity                           | NO                       | YES                   | YES                   |
|              | Ocean salinity                          | YES                      | YES                   | YES                   |
| Other        | Dissolved oxygen                        | YES (Pacific & S. Ocean) | YES                   | YES                   |
|              | Air pollution levels                    | NO                       | NO                    | NO                    |

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*[RM May 13 edits: Inserted Judy's new Sct 8.3 + wildfire text, John's revised Fig 8.4.2 short text in place of Table 8.2.1]*

*[IRC edits May 14: folded the results from the three precipitation extremes from Ross's analysis into each of the already-discussed sections, minor edits]*

*[JC light edits May 14]*

*[RM May 14 condensed Howarth discussion, added summary]*

## **78 Extreme weather in the US and elsewhere**

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### **78.1 Introduction**

High impact weather extremes, usually related to temperature, and/or precipitation and/or excessive wind, often can disrupt infrastructure and therefore endanger human health and thriveability wellbeing. Indeed, the ability of any surface-dwelling species to live productively is somewhat constrained by these extremes which in essence create the bounding limits for survival. The issue is not whether extremes occur, for they are intrinsic to the chaotic climate system. Rather, it is whether there are long-term (decadal scale) changes in the frequency and/or character of extremes ("detection"), as well as the extent to which such changes here is whether these extremes, and their attendant changes in potential danger hazards, may be changing and if so whether the change is in response caused by to anthropogenic emissions increases in infrared-absorbing of greenhouse gases (GHGs) ("attribution"; e.g., IPCC AR6 Seneviratne et al. 2021).

It is naïve to assume that any recent unprecedented extreme event observed recently is caused by human influences on the climate. Unfortunately, that's That assumption is wrong in two ways. First, climate is about the statistical properties of weather over decades, not single events. And second, there are only about 130 years of the reliable Unfortunately, observational records that can be analyzed statistically, extend back only for the sample of time from which we are able to quantitatively analyze variations in extreme events is quite brief, about around 130 years. That brief interval does not. This period certainly does not begin to contain all of the extreme events that the climate system is able to can create naturally on its own. Over geologic time the climate system has generated an (essentially) infinite variety of weather patterns and extremes which that humans have never observed, and thus do not enter our are absent from the databases from which used to determine extreme statistics; are determine d [see *Perils of short data records* below]. Thus, assuming that a For that reason, attributing climate pattern or an extreme event hitherto unprecedented in the record not experienced in our lifetime must therefore be the result of enhanced GHG concentrations requires the assumptions about the smallness magnitude of that natural variations, are insignificant.

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This is especially true for precipitation events. The hydrological literature has long noted the phenomenon of *Long-Term Persistence* (LTP) in rainfall data (Hurst 1951, Cohn and Lins 2005, Markonis and Koutsoyiannis 2015). LTP has a formal mathematical definition but it can be thought of intuitively as the presence of natural variations with strong autocorrelation properties that result in cycle-like behavior on long time scales. The presence of LTP requires very-long data samples records to obtain accurately accurate estimates of variance variability. Analysis of analysis of data samples that are records short relative to the LTP scale will tend to yield underestimate variability, therefore underestimated variances which in turn yields overstating the significance of

<sup>1</sup> For example, under the simplest statistical assumptions there is a 37 percent chance that a 100-year event is NOT present in a given century-long record.

apparent trends and underestimation of the likelihood of extreme events (Cohn and Lins 2005).

A good example of LTP is the eight-century long record of the annual minimum height of the Nile River observed at Roda Island in Cairo (shown below) in Figure 87.1.1. Since human influences on the global climate were negligible before the 20<sup>th</sup> century, the century-scale variability of the thirty-year average is entirely natural; Egyptians of the seventh and eight centuries would have been incorrect to assume that the worsening drought during that time was the “new normal.”

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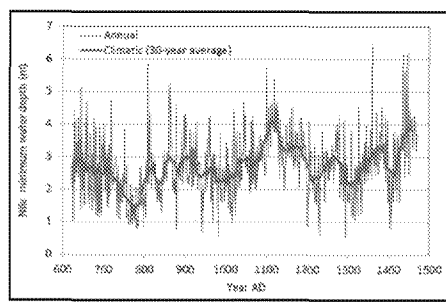


Figure 87.1.1: Nile River discharge [details, source]

With these caveats in mind, we examine the evidence for changes in selected weather and climate extremes. A theme that emerges when reviewing this topic is the wide gap between public perceptions and scientific evidence. It has become routine in media discussions, government and private sector discussions and even in some academic literature to make generalized assertions that extreme weather of all types is getting worse due to GHGs and climate change. Yet expert assessments have not typically drawn such sweeping conclusions and instead have emphasized the difficulty both of identifying specific trends and establishing a causal connection with anthropogenic forcing.

In the sections to follow we cite provide excerpts from various IPCC and NCA assessment reports denoting the sources as follows:

For the benefit of readers who may not have read the relevant reports in the Appendix to this chapter we will begin provide with extended excerpts of these findings from previous IPCC and NCA assessments, then in the remainder of this chapter survey additional data relevant to US and global extreme weather trends.

## 8.2 Review of IPCC and NCA Findings on Extreme Weather

The sources we review will be denoted as follows:

**SREX:** The IPCC *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (2012)

**AR5:** The IPCC *Fifth Assessment Report Working Group 1* (2013).

**AR6:** The IPCC *Sixth Assessment Report Working Group 1* (2021).

NCA17: The US Climate Science Special Report of the Fourth National Climate Assessment (2017)  
Volume I Chapter 6.  
NCA23: The US Climate Science Special Report of the Fifth National Climate Assessment (2023)  
Volume I.

Note that in the excerpts, provided italics are in the original whereas **boldface** emphasis is added.

**8.2.1 Overview Context: IPCC Assessment of signal emergence in extreme weather types (AR6 WG1 Table 12.12)**

This chapter is concerned with detection of trends. Chapter 7 looked at attribution including for extreme weather. Since there is considerable public interest in the question of whether humans are causing trends in extreme weather to get worse it is useful to begin with the summary Table 8.2.1 which reproduces the findings of AR6 Table 12.12 which indicates, for 34 major weather event and impact types, whether a signal of anthropogenic forcing has been detected in the historical record (column 1), whether such a signal is likely to emerge by 2050 under the extreme RCP8.5 scenario (column 2) and whether it is likely to emerge by 2100 under RCP8.5 forcing (column 3). It should be borne in mind that the latter two columns suffer from the deficiencies of GCMs discussed in Chapter XX. And as we discussed in Ch X7 on attribution, AR6 offers conflicting messages about attribution of extreme weather. Nevertheless, we provide this Table for reference context.

Several patterns stand out. First detection of an anthropogenic signal is asserted with *high confidence* in only four of the 34 weather impact categories, and with *medium confidence* in a further four. The IPCC does NOT claim to have detected an anthropogenic signal in the remaining 26 categories. Of the four *high confidence* assertions, two are for changes in average temperatures (air and ocean), which are not measures of extreme weather. Further, two of the four *medium confidence* assertions are related to ocean chemistry and are also not related to extreme weather. The IPCC does NOT assert a detectable human influence on many non-temperature weather features such as wind, precipitation, flooding, and drought.

Second, columns 2 and 3 show that the IPCC expects very few anthropogenic trends to emerge within this century, even under the most extreme forcing scenario. As we discuss in Section 4.2 the RCP8.5 scenario is an implausible high-end storyline, not a "base case" or "business-as-usual" projection. Even so, most weather impacts are not expected to show an anthropogenic signal this century. Natural variability dominates patterns of extreme weather systems and simplistic assertions of trend detection are frequently undermined by regional heterogeneity and trend reversals over time.

| <u>Climate Impact Driver Type</u> | <u>Climate Impact Driver Category</u>         | <u>Already Emerged in the Historical Record?</u> | <u>Emerging by 2050 in Most Extreme CO2 Emissions Scenario?</u> | <u>Emerging by 2100 in Most Extreme CO2 Emissions Scenario?</u> |
|-----------------------------------|-----------------------------------------------|--------------------------------------------------|-----------------------------------------------------------------|-----------------------------------------------------------------|
| <u>Heat &amp; Cold</u>            | <u>Average air temperature</u>                | <u>YES in most regions</u>                       | <u>YES</u>                                                      | <u>YES</u>                                                      |
|                                   | <u>More heat extremes</u>                     | <u>YES in most regions</u>                       | <u>YES in land regions</u>                                      | <u>YES</u>                                                      |
|                                   | <u>Fewer cold extremes</u>                    | <u>YES in a few regions</u>                      | <u>YES in many regions</u>                                      | <u>YES</u>                                                      |
|                                   | <u>Less frost</u>                             | <u>NO</u>                                        | <u>NO</u>                                                       | <u>NO</u>                                                       |
| <u>Wet &amp; Dry</u>              | <u>Average Precip. (Increase or Decrease)</u> | <u>NO</u>                                        | <u>YES (incr) YES (decr)</u>                                    | <u>YES (incr) YES (decr)</u>                                    |
|                                   | <u>River Flooding</u>                         | <u>NO</u>                                        | <u>NO</u>                                                       | <u>NO</u>                                                       |



|              |                                     |                          |                      |                      |
|--------------|-------------------------------------|--------------------------|----------------------|----------------------|
|              | Heavy precipitation & pluvial flood | NO                       | NO                   | YES in a few regions |
|              | Landslide                           | NO                       | NO                   | NO                   |
|              | Aridity                             | NO                       | NO                   | NO                   |
|              | Hydrologic Drought                  | NO                       | NO                   | NO                   |
|              | Agricultural & ecological drought   | NO                       | NO                   | NO                   |
|              | Fire weather                        | NO                       | NO                   | NO                   |
| Wind         | Average wind speed                  | NO                       | NO                   | NO                   |
|              | Severe wind storm                   | NO                       | NO                   | NO                   |
|              | Tropical cyclone                    | NO                       | NO                   | NO                   |
|              | Sand and dust storm                 | NO                       | NO                   | NO                   |
|              | Snow, glacier & ice sheet           | NO                       | YES in a few regions | YES Arctic snow      |
| Snow and Ice | Permafrost                          | YES                      | YES                  | YES                  |
|              | Lake & river ice                    | NO                       | YES                  | YES                  |
|              | Arctic sea ice                      | YES                      | YES                  | YES                  |
|              | Antarctic sea ice                   | NO                       | YES                  | YES                  |
|              | Heavy snowfall and ice storm        | NO                       | NO                   | NO                   |
|              | Hail                                | NO                       | NO                   | NO                   |
| Coastal      | Snow avalanche                      | NO                       | NO                   | NO                   |
|              | Relative sea level                  | NO                       | YES                  | YES                  |
|              | Coastal flood                       | NO                       | NO                   | NO                   |
|              | Coastal erosion                     | NO                       | NO                   | NO                   |
| Open Ocean   | Average ocean temperature           | YES                      | YES                  | YES                  |
|              | Marine heat wave                    | NO                       | NO                   | NO                   |
|              | Ocean acidity                       | NO                       | YES                  | YES                  |
|              | Ocean salinity                      | YES                      | YES                  | YES                  |
|              | Dissolved oxygen                    | YES (Pacific & S. Ocean) | YES                  | YES                  |
| Other        | Air pollution weather               | NO                       | NO                   | NO                   |
|              | Solar or IR radiation at surface    | NO                       | NO                   | NO                   |

**Table 8.2.1. IPCC AR6 summary of the probable emergence of an anthropogenic signal above natural climate variability for all global or regional “climate impact drivers” (CIDs) of concern for humans and ecosystems in response to increasing atmospheric greenhouse gas concentrations (primarily CO<sub>2</sub>).** Source: Table adapted from report of Working Group I, Table 12.12). Red = high confidence; yellow = medium confidence; green = no anthropogenic signal detectable above natural variability (50% confidence).

Taking wind as an example, the IPCC claims that an anthropogenic signal has **NOT** emerged in average wind speeds, severe windstorms, tropical cyclones, or sand and dust storms, and none are expected to emerge this century even under an extreme emissions scenario. The same applies to drought and fire weather. This table alone suffices to illustrate the gap between IPCC expert assessments of extreme weather and discussions in the popular media and political arenas. As we show below the Table reflects longstanding conclusions of the IPCC and other assessment bodies. In the next few sections we will simply present without comment excerpts from past assessment reports.<sup>2</sup> In selecting these excerpts, we’ve focused on the highest-level summaries to avoid accusations of bias through “cherry picking”.

**§7.2 Context: detection is not attribution**

<sup>2</sup> In these excerpts we have added **bold-face** emphasis, while *italicized* emphasis on confidence terms appears in the original sources. Citations in quoted text can be found in the underlying reports but are not reproduced here.

This chapter is concerned with detection of trends. Chapter 79 looked at causal attribution, with Section 79.4 specifically addressing extreme weather. If no trend is detected, then clearly there is no basis for attribution. But even where a trend is observed attribution should not be assumed automatically to follow. Since there is considerable public interest in the question of whether humans are causing trends in extreme weather to get worse, it is useful to recall that AR6 Table 12.12 indicates that, for 34 major weather event and impact types, detection of an anthropogenic signal is asserted with *high confidence* in only four of the 34 weather impact categories, and with *medium confidence* in a further four. The IPCC does not claim to have detected an anthropogenic signal in the remaining 26 categories. Of the four *high confidence* assertions, two are for changes in average temperatures (air and ocean), which are not measures of extreme weather. Also, two of the four *medium confidence* assertions are related to ocean chemistry and are also not related to extreme weather. The IPCC does not assert a detectable human influence on many non-temperature weather features such as wind, precipitation, flooding, and drought.

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### 87.2.73 Hurricanes and Tropical Cyclones

The AR6 assessed provides the following assessment of tropical cyclones (TCs; used here to be synonymous with hurricanes):

AR6: There is *low confidence* in most reported long-term (multidecadal to centennial) trends in TC frequency or intensity-based metrics due to changes in the technology used to collect the best-track data. (IPCC, 2021)

AR6: It is *likely* that the global proportion of major (Category 3–5) tropical cyclone occurrence has increased over the last four decades . . . There is *low confidence* in long-term (multidecadal to centennial) trends in the frequency of all-category tropical cyclones. (IPCC, 2021)<sup>3</sup>

AR6: A subset of the best-track data corresponding to hurricanes that have directly impacted the United States since 1900 is considered to be reliable, and shows **no trend in the frequency of U.S. landfall events**. (IPCC, 2021)

Since 1980, when satellite observations fully covered the global oceans, we have confidence in the numbers of total global hurricanes and major hurricanes (Category 3 and higher). Figure 87.3.1 shows that on average, each year there are about 50 hurricanes, with about 25 reaching major hurricane status (RN-Maue, 2025). Substantial year-to-year and decadal variability is seen; over the time period, there is a slight decreasing trend in the number of hurricanes and a slight but insignificant increasing trend in the number of major hurricanes. From these two trends, it is inferred that there is an overall trend of increasing percentage of major hurricanes, relative to the total number of hurricanes.

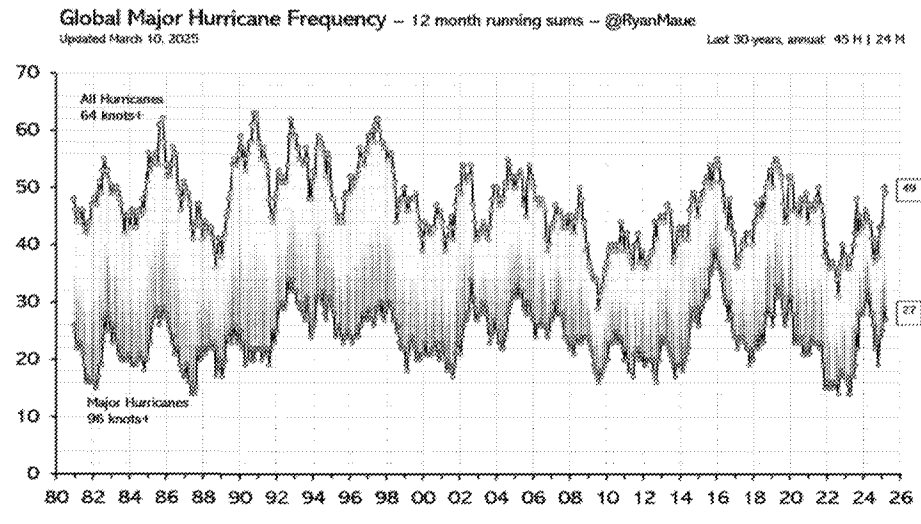
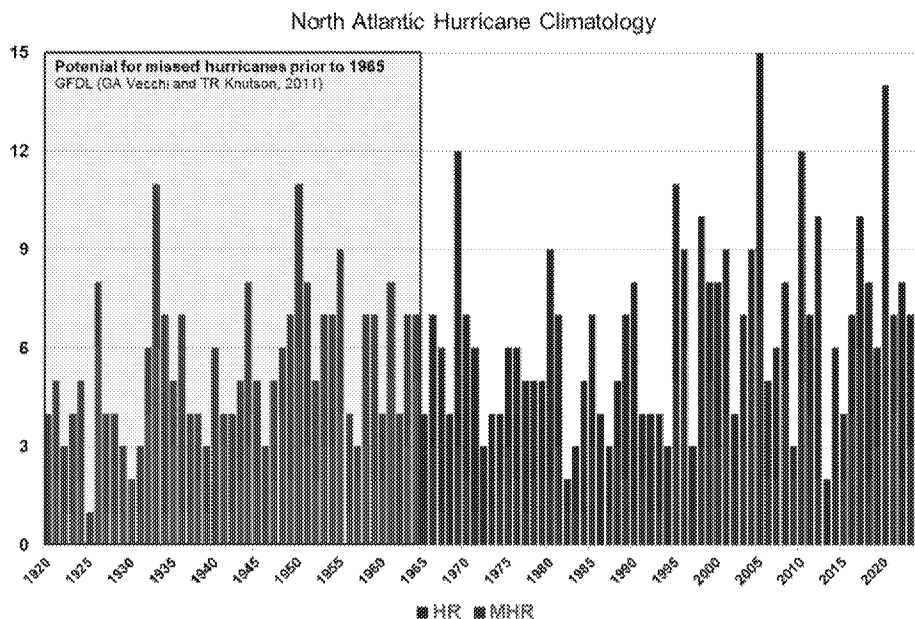


Figure 87.3.1: Global frequency of hurricanes and major hurricanes since 1980.

Global hurricane statistics are dominated by the Northwest Pacific Ocean which accounts for ~35 percent of total global hurricanes whereas the Atlantic accounts for ~15% percent of global

hurricanes (CSU, 2025). Data in the Atlantic Ocean extends further back than in the other ocean basins, and is most relevant to U.S. policy makers.

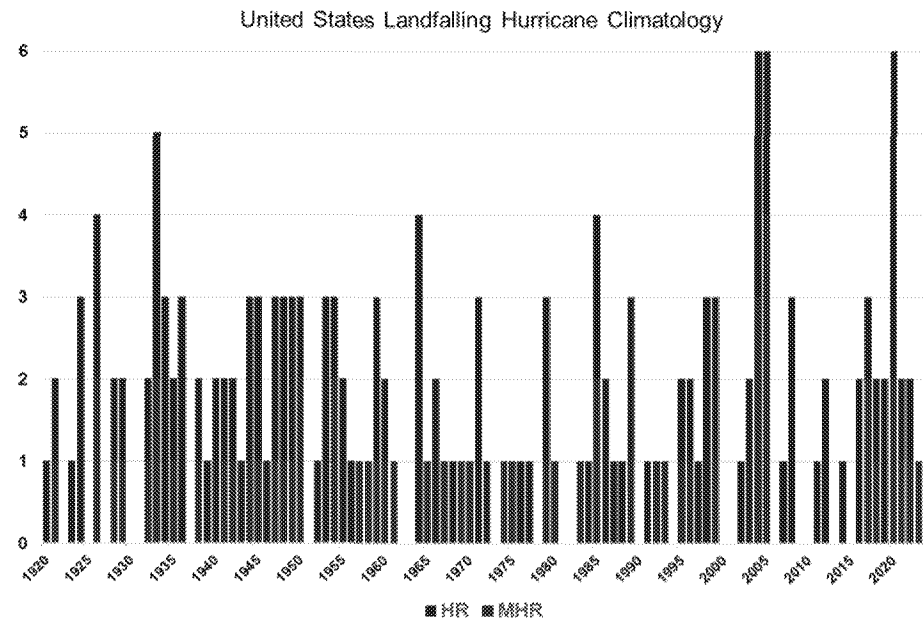
Figure 8.7.3.2 shows the frequency of Atlantic hurricanes (HR) and major hurricanes (MHR; Category 3 and higher) back to 1920. Data prior to 1965 (the onset of satellite observations in the Atlantic, shaded in blue) shows some undercounting, with data prior to 1920 showing substantial undercounting (GA Vecchi and TR Knutson, 2011). All measures of Atlantic hurricane activity show a significant increase since 1970. However, the period from 1971-1994 was a period of exceptionally low activity, with high values of hurricane activity [comparable to the past two decades, even with undercounting] also observed during the 1950's and 1960's, and also even in the 1930's.



**Figure 8.7.3.2:** Atlantic frequency of hurricanes and major hurricanes since 1920. Source (NHC, 2024)

It is seen from Figure 8.7.3.2 that Atlantic hurricanes show strong variations on decadal and multi-decadal time scales in the observed record. These variations are associated primarily with the Atlantic Multidecadal Oscillation (AMO), which is associated with basin-wide sea surface temperature and sea level pressure fluctuations associated with large scale ocean circulation patterns. The AMO was in its warm phase during 1926-1970 and 1995-present; the AMO was in its cool phase during 1971-1994. The greatest impact of the AMO is on the number of major hurricanes (Category 3+). The relationship of the AMO to major hurricane activity in the Atlantic was identified by Goldenberg et al. (2001) to be associated with above normal SSTs and decreased vertical shear associated with the warm AMO (see also GD-Bell and M-Chelliah, 2006; PI-Klotzbach et al., 2018).

Klotzbach et al. (2018) conducted a comprehensive evaluation of the landfalling hurricane data for the Continental U.S. since 1900. Figure 8-7.3.3 updates the Klotzbach et al. analysis through 2024. While the largest numbers of hurricanes are from 2004, 2005 and 2020, the overall trend since 1920 is not statistically significant from zero. Figure 8-7.3.3 also shows the time series for major hurricane landfalls (Category 3-5). The largest year in the record is 2005, with 4 major hurricane landfalls. However, during the period 2006 through 2016, there were no major hurricanes striking the U.S., which is the longest such period in the record since 1920.



**Figure 8-7.3.3:** US landfalling frequency of hurricanes and major hurricanes since 1920. Source (NOAA HRD(a), 2024)

Substantial interannual to multidecadal variability in U.S. landfall activity is seen Figure 7.3.3. in Klotzbach et al. (2018) examined how the landfall counts vary with ENSO (El Niño versus La Niña) and the warm versus cold phases of the Atlantic Multidecadal Oscillation (AMO).

Villarini et al. (2012) provide an analysis of U.S. hurricane landfalls back to 1878. While it is possible that some landfalls were missed in the late 19<sup>th</sup> century owing to sparsely populated regions on the Gulf Coast, it is remarkable that the highest year in the entire record, with 7 landfalls, is 1886.

Table 8-7.3.1 shows the 10 strongest hurricanes (plus ties) to make U.S. landfall. Of the hurricanes that have made landfall with sustained winds greater than 150 mph, only one has occurred in the busy period since 2004 the 21<sup>st</sup> century.

**Table 8.7.3.1** Strongest hurricanes to make landfall along the US coast. Source (NOAA HRD(b), 2024)

| Rank | Year | Landfall Wind (MPH) | Name          |
|------|------|---------------------|---------------|
| 1    | 1935 | 185                 | "Labor Day"   |
| 2    | 1969 | 175                 | Camille       |
| 3    | 1992 | 165                 | Andrew        |
| 4    | 2018 | 160                 | Michael       |
| 5    | 1856 | 150                 | "Last Island" |
| 5    | 1886 | 150                 | "Indianola"   |
| 5    | 1919 | 150                 | -----         |
| 5    | 1932 | 150                 | "Freeport"    |
| 5    | 2004 | 150                 | Charley       |
| 5    | 2020 | 150                 | Laura         |
| 5    | 2021 | 150                 | Ida           |
| 5    | 2022 | 150                 | Ian           |

While an increase in hurricane intensity has long been hypothesized to occur as global sea surface temperatures increase, identification of any significant trend in the hurricane data is hampered by a short data record and substantial natural variability.

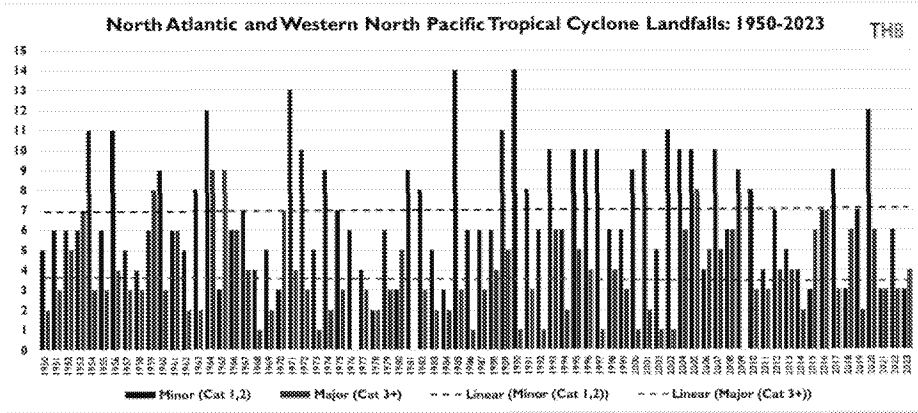
In summary, analyses of both global and regional variability and trends of hurricane activity provide the basis for detecting changes and understanding their causes. The relatively short historical record of hurricane activity, and the even shorter record from the satellite era, is not sufficient to assess whether recent hurricane activity is unusual relative to the background natural variability. Atlantic hurricane processes are influenced substantially by the natural modes of ocean circulation variability in the Atlantic, notably the Atlantic Multidecadal Oscillation. The AR6 assessed this topic as follows:

AR6: There is *low confidence* in most reported long-term (multidecadal to centennial) trends in TC frequency or intensity-based metrics due to changes in the technology used to collect the best-track data. (Chapter 11, p. 1585)

AR6: It is *likely* that the global proportion of major (Category 3–5) tropical cyclone occurrence has increased over the last four decades. There is *low confidence* in long-term (multidecadal to centennial) trends in the frequency of all-category tropical cyclones. (SPM A.3.4)

AR6: A subset of the best-track data corresponding to hurricanes that have directly impacted the United States since 1900 is considered to be reliable, and shows **no trend in the frequency of U.S. landfall events**. (Chapter 11 Summary, p. 1585)

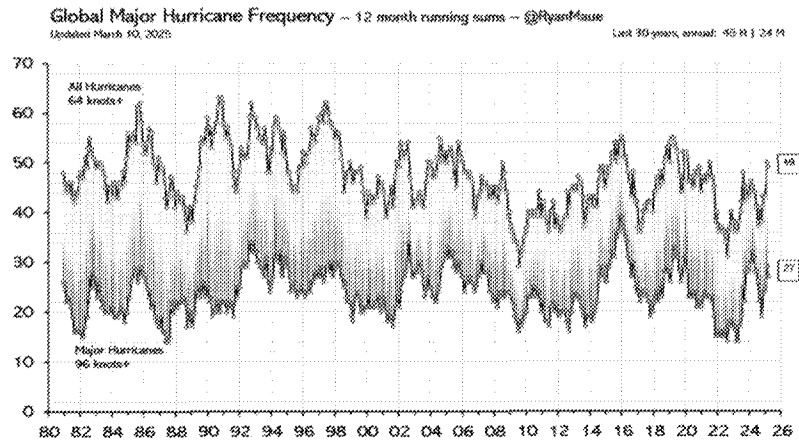
Hurricane strength records for the North Atlantic and the Western Pacific go back to 1950 and the record does not show an increase in either total or major TCs. Figure 8.3.1 was published by Roger Pielke Jr. as an update to the Best Track data series originally presented in Weinkle et al. (2012).



**Figure 8.3.1. Tropical Cyclone Landfalls.** Source: [HYPERLINK "<https://rogerpielkejr.substack.com/p/global-tropical-cyclones>"]. Weinkle et al. (2012)

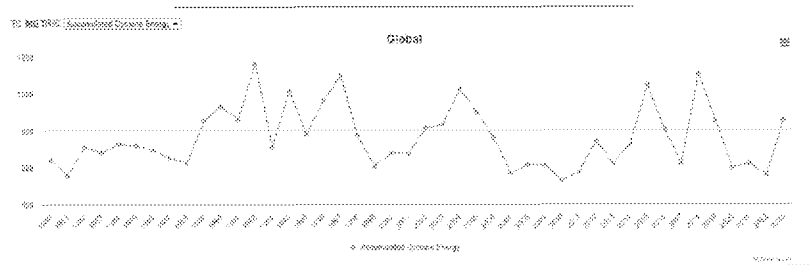
Similarly, Figure 8.3.2 (Maue 2025, [HYPERLINK "<https://climatlas.com/tropical/>"]) shows that both all hurricanes and major hurricanes have not become more common since 1980, the period of rapidly growing human influences. In fact, both numbers have trended down slightly since the 1990s:

Commented [A2]: Cite the Climate Atlas of Dr. Ryan Maue



**Figure 8.3.2: Global hurricane frequency.** Source: Maue (2025)

A metric that combines the number, duration, and strength of TCs is the Accumulated Cyclone Energy (ACE) Index maintained at Colorado State University, shown in Figure 8.3.3. It clearly shows no long-term increase, in fact declining slightly since 1990.



**Figure 8.3.3: Global Accumulated Cyclone Energy.** Source: Klotzbach (2025)  
[HYPERLINK "<https://tropical.atmos.colostate.edu/Realtime/index.php?arch&loc=global>"]

Note that Tu et al. (2024) report that the Power Dissipation Index (PDI), another different measure that combines hurricane number, duration, and strength, has either remained unchanged or has declined in all global oceanic basins since the mid-1990s.

Today's global climate simulations are too coarse to project changes in TCs directly. Rather, projections are derived from finer "downscaled" simulations or proxies involving sea surface temperatures, winds, and aerosols. By those methods, a warming climate is expected to show declining hurricane formation rates (Chand et al. 2022). Climate models also project fewer Tropical Cyclones under future global warming, and even though models project they will increase in strength, the annual averages of rainfall maxima decline (Stansfield et al. 2020).

### 8.3 Tornadoes SREX (p. 159):

There have been no significant trends observed in global tropical cyclone frequency records, including over the present 40-year period of satellite observations (e.g. Webster et al., 2005). Regional trends in tropical cyclone frequency have been identified in the North Atlantic, but the fidelity of these trends is debated (Holland and Webster, 2007; Landsea, 2007; Mann et al., 2007a). Different methods for estimating undercounts in the earlier part of the North Atlantic tropical cyclone record provide mixed conclusions (Chang and Guo, 2007; Mann et al., 2007b; Kunkel et al., 2008; Vecchi and Knutson, 2008). Regional trends have not been detected in other oceans (Chan and Xu, 2009; Kubota and Chan, 2009; Callaghan and Power, 2011). It thus remains uncertain whether any observed increases in tropical cyclone frequency on time scales longer than about 40 years are robust after accounting for past changes in observing capabilities (Knutson et al., 2010).

### AR5 (pp. 216-17):

Current data sets indicate no significant observed trends in global tropical cyclone frequency over the past century and it remains uncertain whether any reported long-term increases in tropical cyclone frequency are robust, after accounting for past changes in observing capabilities (Knutson et al., 2010). No robust trends in annual numbers of tropical storms, hurricanes and major hurricanes counts have been identified over the past 100 years in the North Atlantic basin. Measures of land-falling tropical cyclone frequency



(Figure 2.34) are generally considered to be more reliable than counts of all storms which tend to be strongly influenced by those that are weak and/or short lived. Callaghan and Power (2011) find a statistically significant decrease in Eastern Australia land-falling tropical cyclones since the late 19th century although including 2010/2011 season data this trend becomes non-significant (i.e. a trend of zero lies just inside the 90% confidence interval). Significant trends are not found in other oceans on shorter time scales (Chan and Xu, 2009; Kubota and Chan, 2009; Mohapatra et al., 2011; Weinkle et al., 2012), although Grinsted et al. (2012) find a significant positive trend in eastern USA using tide gauge data from 1923–2008 as a proxy for storm surges associated with land-falling hurricanes. Differences between tropical cyclone studies highlight the challenges that still lie ahead in assessing long-term trends.

In summary, this assessment does not revise the SREX conclusion of *low confidence* that any reported long-term (centennial) increases in tropical cyclone activity are robust after accounting for past changes in observing capabilities. More recent assessments indicate that it is *unlikely* that annual numbers of tropical storms, hurricanes and major hurricanes counts have increased over the past 100 years in the North Atlantic basin. Evidence, however, is for a virtually certain increase in the frequency and intensity of the strongest tropical cyclones since the 1970s in that region.

AR6 (p.1585)

There is *low confidence* in most reported long-term (multidecadal to centennial) trends in TC frequency or intensity-based metrics due to changes in the technology used to collect the best-track data. This should not be interpreted as implying that no physical (real) trends exist, but rather as indicating that either the quality or the temporal length of the data is not adequate to provide robust trend detection statements, particularly in the presence of multidecadal variability.

There are previous and ongoing efforts to homogenize the best-track data (Elner et al., 2009; Kossin et al., 2013, 2020; Choy et al., 2015; Landsea, 2015; Emanuel et al., 2018) and there is substantial literature that finds positive trends in intensity-related metrics in the best-track during the “satellite period”, which is generally limited to the past ~40 years (Kang and Elner, 2012; Kitchawa et al., 2012; Kossin et al., 2013, 2020; Mei and Xie, 2016; Zhao et al., 2018; Taulyale and Tsuboki, 2019). When best-track trends are tested using homogenized data, the intensity trends generally remain positive, but are smaller in amplitude (Kossin et al., 2013; Holland and Bruyère, 2014). Kossin et al. (2020) extended the homogenized TC intensity record to the period 1979–2017 and identified significant global increases in major TC exceedance probability of about 6% per decade.<sup>2</sup> In addition to trends in TC intensity, there is evidence that TC intensification rates and the

<sup>2</sup>The underlined text referenced a study (Kossin et al. 2020) that later retracted a portion of its findings. Those authors assembled a data set on global TC incidence spanning 1979 to 2017 from which they claimed that the global fraction of TCs reaching major status (Cat 3–5) rose from 27% during 1979–1997 to 31% during 1998–2017 and that the increase was statistically significant. However, closer examination of their results showed a significant increase only in the North Atlantic (18% to 34%) whereas changes in all other basins (Eastern Pacific, Western Pacific, North Indian, South Indian, South Pacific) were not statistically significant. In a subsequent correction ([HYPERLINK "https://www.pnas.org/doi/10.1073/pnas.2021573117"]), Kossin et al. stated that the global probability of observing a major TC rose from 34% during 1979–1997 to 37% in the later period and that the evidence for statistical significance was now weaker. Nevertheless, the authors claimed that the correction did not affect their conclusions.

frequency of rapid intensification events have increased within the satellite era (Kishtawal et al., 2012; Balaguru et al., 2013; Bhatia et al., 2013). The increase in intensification rates is found in the best-track as well as the homogenized intensity data.

A subset of the best-track data corresponding to hurricanes that have directly impacted the United States since 1900 is considered to be reliable, and shows no trend in the frequency of U.S. landfall events (Knutson et al., 2019).

AR6: [O]bservational trends in tornadoes, hail, and lightning associated with severe convective storms are **not robustly detected** due to insufficient coverage of the long-term observations. There is *medium confidence* that the mean annual number of tornadoes in the USA has remained relatively constant. (Chapter 11, section 11.7.3, p. 1594)

As noted there is no evidence of trends in US tornadoes or extreme convective storms. Extreme precipitation will be discussed further below.

#### 8.7.34 Temperature extremes

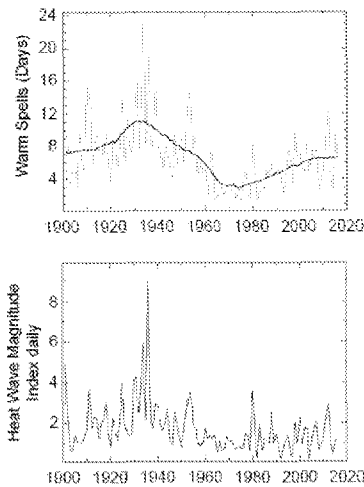
The AR6 assessment focused on the period after 1950 and reported increasing trends in heatwave frequency and intensity. The NCA17 however noted that heatwave activity in the US reached a peak in the 1930s.

AR6: "It is *virtually certain* that hot extremes (including heatwaves) have become **more frequent** and **more intense** across most land regions since the 1950s, while cold extremes (including cold waves) have become less frequent and less severe" (SPM, A3.1)

AR6: "In North America, there is very robust evidence for a *very likely* increase in the intensity and frequency of hot extremes and decrease in the intensity and frequency of cold extremes for the whole continent, though there are substantial spatial and seasonal variations in the trends. Minimum temperatures display warming consistently across the continent, while there are more contrasting trends in the annual maximum daily temperatures in parts of the USA." (Chapter 11, p 1550)

NCA17: "Changes in warm extremes are more nuanced than changes in cold extremes. For instance, the warmest daily temperature of the year **increased** in some parts of the West over the past century, but there were **decreases** in almost all locations east of the Rocky Mountains. In fact, all eastern regions experienced a net **decrease**, most notably the Midwest (about 2.2°F [1.2°C]) and the Southeast (roughly 1.5°F [0.8°C])." (pp. 190-191)

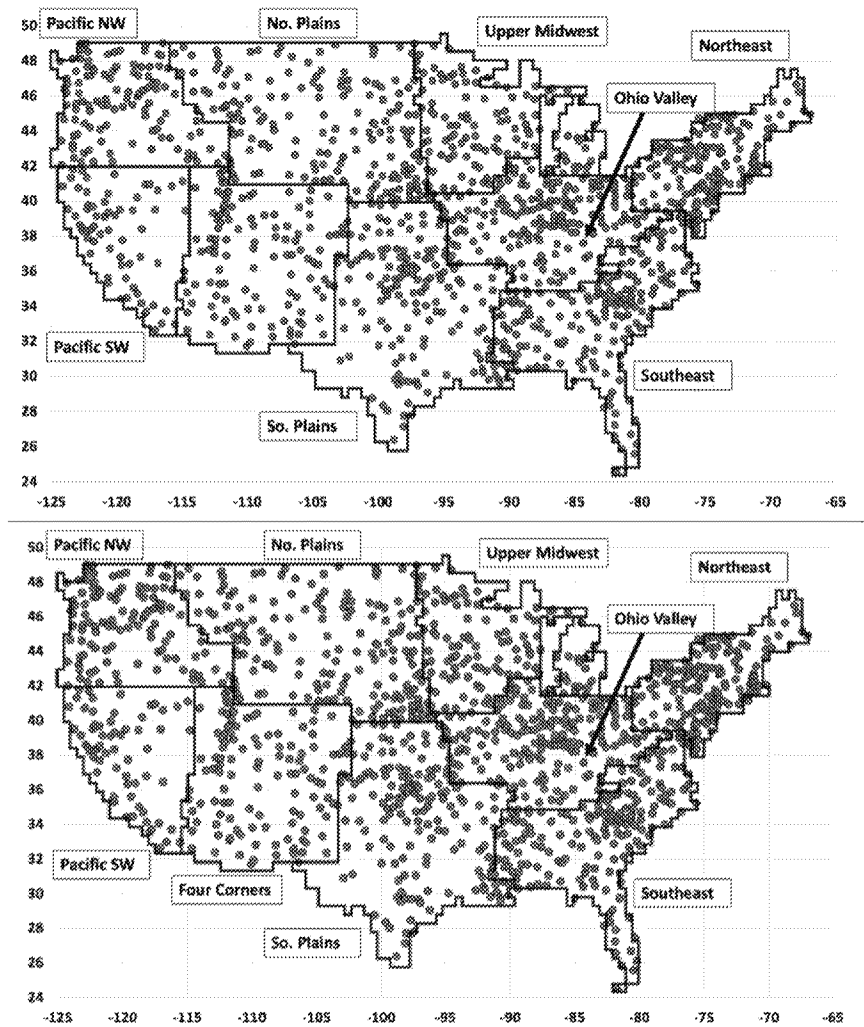
NCA17: "Since the mid-1960s, there has been only a very slight increase in the warmest daily temperature of the year (amidst large interannual variability). Heat waves (6-day periods with a maximum temperature above the 90th percentile for 1961–1990) increased in frequency until the mid-1930s, became considerably less common through the mid-1960s, and increased in frequency again thereafter. As with warm daily temperatures, heat wave magnitude reached a **maximum in the 1930s**." (pp. 190-191)



**Figure 8.7.34.1:** US Heat waves since 1900. Source: NCA17 Figure 6.4

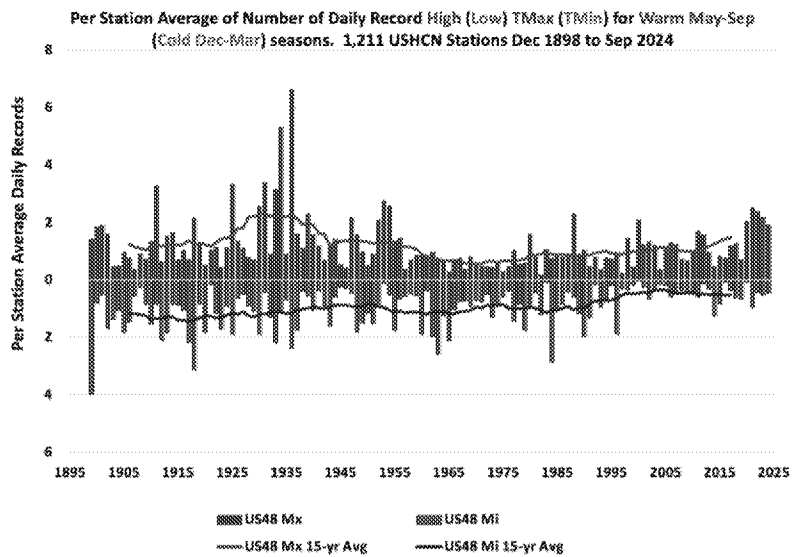
#### 8.7.34.1 Temperatures in the US are becoming less extreme

Daily maximum temperatures in the warm season (TMax, May-Sep) and daily minimum temperatures in the cold season (TMin, Dec-Mar) are available beginning in Dec 1898 (126 years). The dataset consists of 1,211 CONUS stations designated as United States Historical Climate Network or USHCN stations (see Figure 8.7.34.42; Quinlan et al. 1987, Karl et al. 1990). These stations were selected by NOAA as having the fewest problematic issues with gaps, station moves and instrument changes. Where gaps still exist, nearby stations (bias-corrected) were merged so that the median volume of data available for a station is 98%. Although there are certainly errors in the dataset, with over 1,000 stations we can have relatively high confidence in any underlying signal that might be discovered.



**Figure 8-7.34.12** Locations of USHCN temperature stations. Source: USHCN.

We begin with the question of whether the occurrence of daily record high or low temperatures changed has changed since Dec 1898. Each warm-season has 153 days (1 May to 30 Sep) and each cold-season has 122 days (1 Dec to 31 Mar). For each station and day, we calculated the year in which the record highest (lowest) temperature occurred. With 126 years of observations, if there were no temperature trends over time, the expected number of records for TMax would be 1.21 ( $=153/126$ ) per station per year and for TMin 0.96 ( $=122/126$ ) per station per year. Figure 8-7.4-134.3 indicates the observed distribution in time of the occurrence of these extreme events.



**Figure 8-7.34.23** Number of daily record High (red) and Low (blue) for warm and cold seasons in the CONUS. The lines represent the 15-year running, centered average. Source: 1,211 USHCN stations supplemented as needed to achieve a minimum of 92% of observations in the 126-year period since Dec 1898.

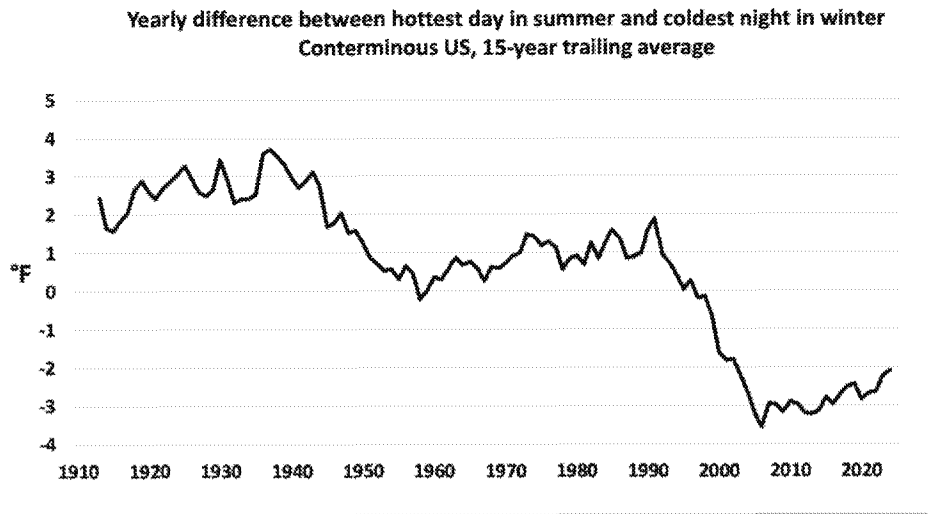
The results indicate a common feature in many metrics of warm-season extremes in the CONUS - the exceptional heat of the 1920s and especially the 1930s, peaking in 1936. On a per-station average, 60% of the TMax records and 59% of the TMin records occurred in the first half of the period (1899-1961).

On the cold side, the Valentine's Day Arctic outbreak in Feb 1899 stands as the most extensive cold extreme experienced by the CONUS, with 1917 in 2<sup>nd</sup> place. The frequency of cold records has declined, especially over the last quarter of the period in which only 13% of the extreme cold events were measured. In contrast, 25% of the extreme TMax records were achieved in the last quarter, in accordance with statistical expectations. These general features have been noted in past assessments (see above, IPCC AR5, IPCC AR6, NCA4, NCA517). Combining the two records the overall reduction in numbers of both cold and hot extremes over the past century indicates a climate less prone to extremes.

This pattern is also shown in Figure 8-7.34.343. For each station and for each year the hottest warm season and coldest cold-season temperatures were calculated and converted to anomalies relative to the station's long-term warm and cold season (respectively) averages. Then the differences between these were computed by station and geographically-averaged over all stations, thus yielding an

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annual measure of the expected range of local extreme temperatures for each year. Figure 8.7.4.411 shows the 15-year trailing average of this measure, which has clearly declined over the past century.



**Figure 8.7.4.411.** 15-year trailing average of the difference each year of each station's hottest warm-season TMax and coldest cold-season TMin relative to the long-term average. Source: USHCN, author calculations.

The average difference for each station between the hottest summer TMax and coldest winter TMin has declined by about 5°F in the past 126 years. The decline is due mostly to warmer winter TMin, but a decline in the magnitude of summer TMax is also a factor. The rise in TMin has been strongly related to the growing presence of manufactured surfaces around the weather stations over the last 100+ years (the so-called urban heat island effect; Spencer et al. 2025).

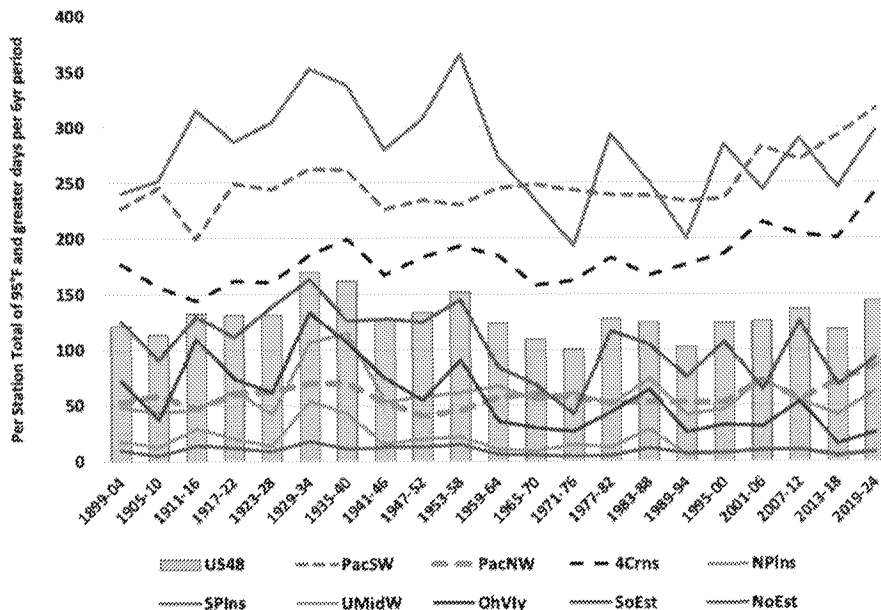
Summarizing Figures 8.7.4.134.23 and 8.7.4.2.3.4.4, in summary, while temperature extremes are regularly experienced in the US and attract a great deal of media attention, long term records show the US climate has become less extreme over time (milder) when measured in terms of the range between warm season maxima and cold season minima.

#### 8.7.4.4.2 Exceedances of a heat threshold

Under the heading of "The Risk of Temperature Extremes is Changing", the most recent US National Climate Assessment report (NCA235) notes the increase in a threshold metric of number of days at or above 95°F, stating,

"The western US has been particularly affected by extreme heat since the 1980s ... experiencing a larger increase in days over 95°F, as would be expected given the greater warming in that region relative to the eastern US. Several major heatwaves have affected the US since 2018, including a record-shattering event in the Pacific Northwest in 2021."

Are the occurrences of 95°F days changing? In a climate as varied as that of CONUS, threshold statistics can be misleading. A region with many stations that have near 95°F TMax average temperatures in the summer might see large swings in the metric when only small changes in average temperature occur. Elsewhere with stations that either rarely or virtually always achieve 95°F TMax temperatures, a small change will not impact the results much at all. In the past 126 years, the average CONUS station experienced 129 days exceeding 95°F per 6-yr period, but the regional values range from 278 in the Southern Plains to 9 in the Northeast. Thus, one needs to view such threshold analyses with caution.



**Figure 8.7.4.334.45.** Total number of days  $\geq 95^{\circ}\text{F}$  in 6-yr periods, US 48 (bars) and regions (lines). Interval is 6-years as this is divisible into 126. Source: USHCN, author calculations.

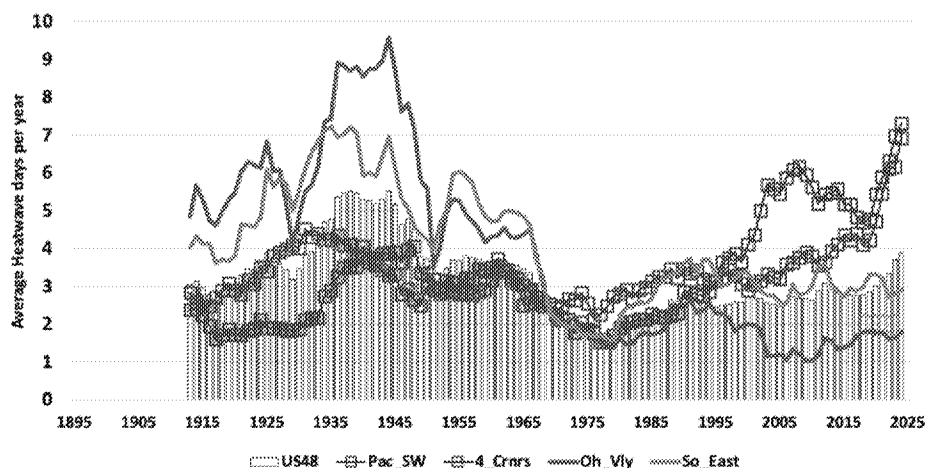
In Fig. 8.7.4.334.45 we see that only three of the nine regions, all in the West, have experienced upward trends in the number of 95°F or hotter days (dashed lines). The CONUS as a whole has not, and the other six regions have experienced declines.

The Pacific NW heatwave of 2021 is referenced as often in the NCA523 claim, an event we examine more closely in Section 69.4. The evidence indicates that it was a “black swan” event, i.e., a single, unprecedented event in the record, not part of a pattern of increasing extreme heat. For example, the 5-day average tropospheric grid-point temperature anomaly over the Pacific NW during that event was +10.8 C, the most extreme NH Northern Hemisphere grid point summer anomaly in the 46 years from over 4 million grid values. In contrast, the global temperature anomaly during that time was virtually zero (+0.03 C, Mass et al. 2024).

The heading “The Risk of Temperature Extremes is Changing” WHERE IS THIS HEADING FROM – Perhaps NCA23? suggests positive trends are now being observed in threshold temperatures on a widespread basis, but that is not evidenced in the combined CONUS results of the figures above.

#### 8.7.4.334.3 Heatwaves

Heatwaves (consecutive days that exceed an extreme threshold) have a greater societal impact than a single daily record temperature. We measure “Heatwave Days” here as the count of all days in May-Sep each year that exceed the 90<sup>th</sup> percentile and that lie within a run period of at least six consecutive days. This is equivalent to the method used in NCA517, except that the reference period here is the entire record 1899-2024, while NCA517 truncated the reference period to 1961-1990, a cool time which was a cool period. That truncation boosts positive results (days exceeding the 90<sup>th</sup> percentile) in periods warmer than the reference period, especially starting in 1960 and moving to the present (see *Urban Influences* below).



**Figure 8.7.4.334.56** 15-year trailing average of number of heatwave days per year per station in the CONUS (bars) and four regions: Pac SW (purple squares, CA, NV), 4 Crnrs (red squares, AZ,NM,UT,CO), Oh Vly (blue, MO, IL, KY, TN, IN, OH, WV) and So East (green, MS, AL, GA, FL, SC, NC, VA).



Figure 8.7.4.434.56 indicates again the excessive heat of the first half of the 20<sup>th</sup> century, primarily in the eastern two-thirds of the nation, as seen in the regional values for the Ohio Valley and the Southeast as examples. The West has seen a recent increase of heatwave days and the two regions with the highest number are shown, the Pacific Southwest and the Four-Corners (NCA523). This indicates that the background warm season circulation favored heatwaves in the eastern portions of the country in the first half of the 20<sup>th</sup> century, but in the 21<sup>st</sup> century the patterns have favored heatwaves in the West. For CONUS as a whole, heatwaves are no more common today than they were a century ago.

Of interest here is the regional variation of this metric. The four northern regions (Pacific NW, Northern Plains, Upper Midwest, and Northeast) on average experience 15 to 27 heatwave days per 15-year period. In contrast, the five southern regions (Pacific Southwest, 4-Corners, Southern Plains, Ohio Valley and Southeast) see 37 to 54 such days, essentially twice as many. This suggests the summer circulation pattern is more prone to stationary events in the southern regions while transient systems in the northern regions are more common and thus cut short these potentially longer events.

#### 8.7.34.4 Urban influences

The NCA523 directs readers to the website [HYPERLINK "https://www.globalchange.gov/indicators/heat-waves"] (USGCRP 2023) to view the number of urban heatwaves by decade from the 1960s. The figure shows a monotonic increase in each decade from 2 occurrences per year in the 1960s to 6 in the 2020s. The definition of a heatwave is an unusual but practical measure of human discomfort - a period of at least 2 consecutive days when the minimum apparent temperature (combination of temperature and humidity) exceeds the 85<sup>th</sup> percentile. Note too, the dataset is limited to the 50 largest U.S. cities.

These increasing values since 1960 presented in USGCRP (2023) are entirely reasonable, but are unrelated to GHG emissions for at least two reasons. Urbanization in these cities is a major factor in the rise of TMin relative to co-located TMax and relative to TMin at rural stations. Also, the 1960s was the coldest decade and 1970s the second coldest decade since the 1910's, so this starting date preconditions the time series to show increases. This does not dismiss the real rise in nighttime temperatures in major U. S. cities and the societal impacts associated with these changes. However, we note for a variety of reasons, that summer TMax (especially in rural areas) serves as better response variable for detecting potential changes in heatwaves influenced by changes in the background climate due, for example, to increasing GHGs (Christy et al. 2009). For the CONUS as a whole, the evidence in this section suggests GHG emissions have had little-to-no effect on heatwaves.

#### 8.4 Tornadoes

AR6: [O]bservational trends in tornadoes, hail, and lightning associated with severe convective storms are **not robustly detected** due to insufficient coverage of the long-term observations. There is *medium confidence* that the mean annual number of tornadoes in the USA has remained relatively constant. (Chapter 11, section 11.7.3, p. 1594)

As noted there is no evidence of trends in US tornadoes or extreme convective storms. Extreme precipitation will be discussed below.

#### **8.7.455 Extreme precipitation**

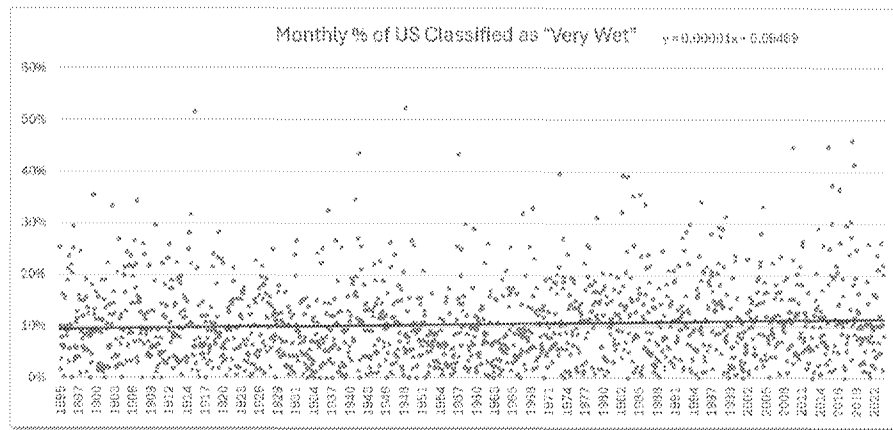
The IPCC AR6 assessed that an increase in heavy precipitation has been observed in data starting in the 1950s.

AR6: "The frequency and intensity of heavy precipitation events have **increased** since the 1950s over most land area for which observational data are sufficient for trend analysis (high confidence)." (SPM A3.2)

AR6: "In North America, there is robust evidence that the magnitude and intensity of extreme precipitation has *very likely* **increased** since the 1950s. Both [one-day maxima] and [5-day maxima] have significantly increased in North America during 1950-2018 "(Chapter 11, p. 1560)

However other data sources indicate less evidence of increasing extreme precipitation when examined over a longer time scale.

Figure 8.7.3-845.1 shows that US long term data from NOAA (1895-2023) shows an insignificantly increasing tendency toward extreme wetness (+0.001% per year)



**Figure 8.7.45.1: Longterm US wetness (%).** Source: NOAA [HYPERLINK "<https://www.ncei.noaa.gov/access/monitoring/uspa/wet-dry/0>"]

Because precipitation involves a discrete phase change (water vapor to liquid), it is ~~stochastic and episodic in character and requires careful statistical treatment to understand variability over long time periods (see 8.7.1 Introduction)~~. The US National Climate Assessments (NCA417, NCA523) have highlighted an increase in the occurrence of the heaviest precipitation events (defined in different ways) primarily in the eastern half of the CONUS, especially the Northeast, when starting the analysis in either 1901 or 1958. Interestingly, the regional variations indicate that the largest increases in

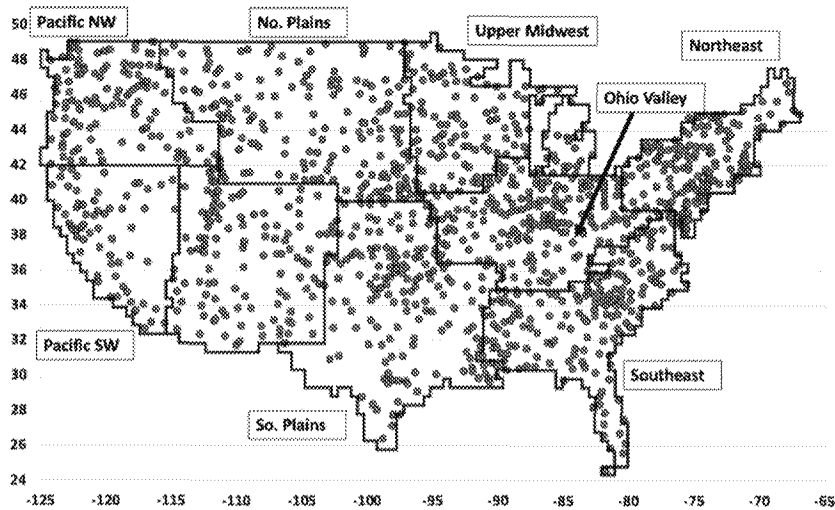
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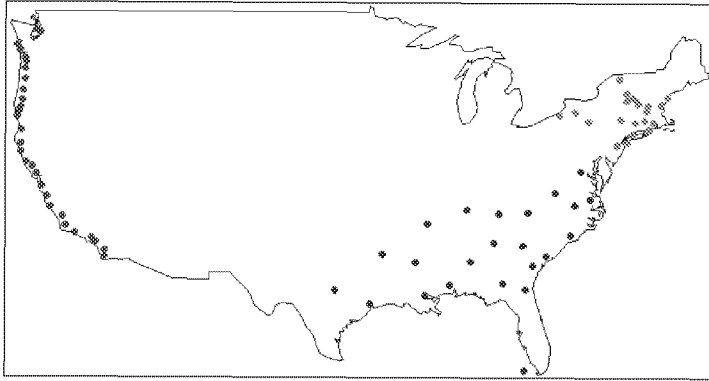
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extreme events are in the Northeast and the smallest in the West, a trend pattern counter to the changes in temperature extremes.



McKittrick and Christy (2019) examined long-term and consistent station observations of extreme daily precipitation to test some of these NCA claims for the Southeast and West Coast. When the time series were extended back in time (as far as 1872 in some cases) or when starting later (1978), there were no significant trends for either region.

For this report we updated these findings with similarly constructed observations from 29 stations on the CONUS Pacific Coast (1893ff from San Diego, CA to Blaine, WA) and ~24 stations in the humid Southeast (1872ff from Austin, TX to Washington, DC), and also adding 21 stations in the Northeast (1888ff from Buffalo, NY to Gardiner, ME). The locations are shown in Figure 7.5.2. The results of applying the analysis of McKittrick and Christy (2019) were as follows for each region, then ; indicating the statistical updates followed by further explanations.



map of stations - RM]

[will generate

Figure 7.5.2: Locations of precipitation monitoring stations used in this report. Green: Pacific coast  
Blue: Northeast. Red: Southeast.

Pacific region:

- Average precipitation trend is significant (downwards) in Astoria, insignificant elsewhere.
- The trend in rainfall variance is positive and significant in Big Sur, insignificant elsewhere.
- The trend in daily maximum precipitation is positive and significant in Aberdeen and Big Sur and negative and significant in Newport (insignificant elsewhere).
- Averaged over all stations in the region none of these three trend parameters is statistically significant.

Southeast region:

- The trend in average precipitation is positive and significant in Mobile and Quitman, insignificant elsewhere.
- The trend in rainfall variance is positive and significant in Mobile, insignificant elsewhere.
- The trend in daily maximum precipitation is positive and significant in Vicksburg and Norfolk, insignificant elsewhere.
- Averaged over all stations in the region none of these three trend parameters is statistically significant.

Northeast region:

- The trend in average precipitation is positive and significant in 9 of 21 locations and in the region averaged overall.
- The trend in rainfall variance is positive and significant in Portland, Albany and Buffalo, insignificant elsewhere.
- The trend in daily maximum precipitation is positive and significant in Portland and Gardiner, insignificant elsewhere.
- Averaged over all stations in the region the trend parameters for variance and maximum precipitation are not statistically significant.

Pacific Coast heavy rainfall events

- Average precipitation trend is significant (downwards) in Astoria OR; insignificant elsewhere.
- The trend in rainfall variance is positive and significant in Big Sur CA; insignificant elsewhere.
- The trend in daily maximum precipitation is positive and significant in Aberdeen WA and Big Sur CA and negative and significant in Newport OR (insignificant elsewhere).
- Averaged over all stations in the region, none of these three trend parameters is statistically significant.

The Pacific Coast receives considerable precipitation from Atmospheric River (AR) events which often last more than a day or two (e.g., Gershunov et al. 2017, Pan et al. 2024). The worst-known such series of events in recent history was the so-called ARekStorm that occurred between December 1861 and January 1862, which dumped nearly 10 feet of rain in parts of California and submerged the entire Central Valley for weeks under as much as 15 feet of water (Brewer 1930, Null and Hulbert 2007). Additionally, Paleoclimate research has found six megastorms more severe than 1861–1862 in California during the last 1800 years, occurring at intervals of 300 years or so (Porter et al. 2011).

#### SIDEBAR: Perils of short data records

San Francisco provides a good case study of the limitation of using short historical samples to characterize natural variability of extreme events. Suppose we use a 130-year sample of daily San Francisco precipitation from 1895 to 2024 and we look for 3-day, 5-day, 14-day and 30-day rainfall records. The results are as shown in Table 8.7.2.

| Event  | Record (inches) | Year |
|--------|-----------------|------|
| 3-day  | 6.94            | 2023 |
| 5-day  | 8.55            | 2023 |
| 14-day | 12.62           | 2023 |
| 30-day | 18.93           | 1998 |

Table 8.7.2: Extreme rainfall records, San Francisco, 1895-2024.

The records all cluster in the more recent data. 2023 appears to be an exceptional year and since it is near the end of the sample, it might suggest that the climate has shifted into a more hazardous state, perhaps as a result of human influences. [Note: "2023" indicates the event occurred in the water-year of Aug 2022 to Jul 2023.]

But the picture is very different if we use a sample that begins 45 years earlier, in 1850. Table 8.7.3 shows that the record-setting events then all happened in the 1860s. Furthermore 2023 is now not even in 2<sup>nd</sup> place but falls to 3<sup>rd</sup> or 4<sup>th</sup> place. Also, comparing the records of the two charts the extreme precipitation events in 1862 and 1867 involved considerably more rainfall than the 1998 and 2023 events, with 14- and 30-day totals about 50 percent higher.

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| Event  | Record (inches) | Year | Rank of 130-yr extreme |
|--------|-----------------|------|------------------------|
| 3-day  | 8.85            | 1867 | 3                      |
| 5-day  | 9.80            | 1867 | 3                      |
| 14-day | 19.05           | 1862 | 4                      |
| 30-day | 28.25           | 1862 | 2                      |

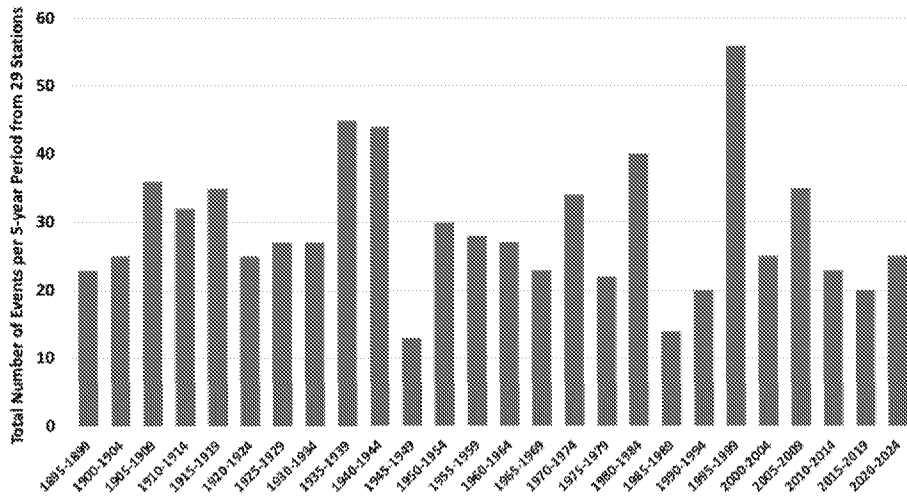
Table 8.7.3: Extreme rainfall records, San Francisco, 1850-2024.

The range of natural variability is made even more remarkable when paleoclimate evidence is examined. Porter et al. (2011) discovered that in the past 1800 years at least six megastorms were more intense than the devastating 1861-62 ARrkStorm that struck the region. Evidently such extreme events, “unprecedented” in our 1895-2024 sample, have impacted the region about every 300 years, though not since 1895.

This example illustrates the limitations of using relatively short climate periods (~130 years) to assess the character and range of natural variability in general and of extreme events in particular. Accurate representation of the full range of natural variability is necessary for any attribution analyses (see 6.4). Infrastructure planners, emergency management institutions and attribution scientists would understand the significant mischaracterization of the magnitude of a future extreme if based only on the last 130 years. In this case, a single time-sample of 130 years provides an underestimation of the extreme value by up to 50% determined when adding only 45 more years of observations. Compared to millennial-scale paleoclimate evidence, an even greater underestimation would occur. An important lesson is that the climate can deliver great surprises on its own, even without human influences.

We examine occurrences of 5-day deluges as follows. Taking the Pacific coast as an example, in a 130-year span there are 26 5-year intervals. At each location we computed the 5-day precipitation totals throughout the year and selected the 26 highest values across the sample. A single year may have more than one of the 26 heaviest. Each of those can be thought of as 1-in-5yr events. If there are no trends in precipitation then the total number of these events across all stations should be evenly spread out over the years. In Fig. 7.5.3 we show the distribution in time of these events for the Pacific coast. The deluges associated with the massive 1997-98 El Niño event are readily apparent. While erratic, as is typical of these types of precipitation metrics, there is no indication of a tendency to become more frequent over time.

We examine occurrences of 5-day deluges as follows. In a 130-year span there are 26 5-year intervals. At each location we computed the 5-day precipitation totals throughout the year and selected the 26 highest values. A single year may have more than one of the 26 heaviest. Each of those can be thought of as 1-in-5yr year events. If there are no trends in precipitation then the total number of these events across all stations should be evenly spread out over the years. In Fig. 8.7.4.55.1 we show the distribution in time of these events. The deluges associated with the massive 1997-98 El Niño event are readily apparent. While erratic, as is typical of these types of precipitation metrics, there is no indication of a tendency to become more frequent over time.



**Figure 7.5.3.** The time distribution by 5-year periods of the 26 heaviest (1-in-5 yr) occurrences for 29 stations on the Pacific coast. ]

**Figure 8.7.5.24.5.** The time distribution by 5-year periods of the 26 heaviest occurrences for each station (i.e., nominal 1-in-5 year event) for stations along the Pacific Coast of the CONUS. ]

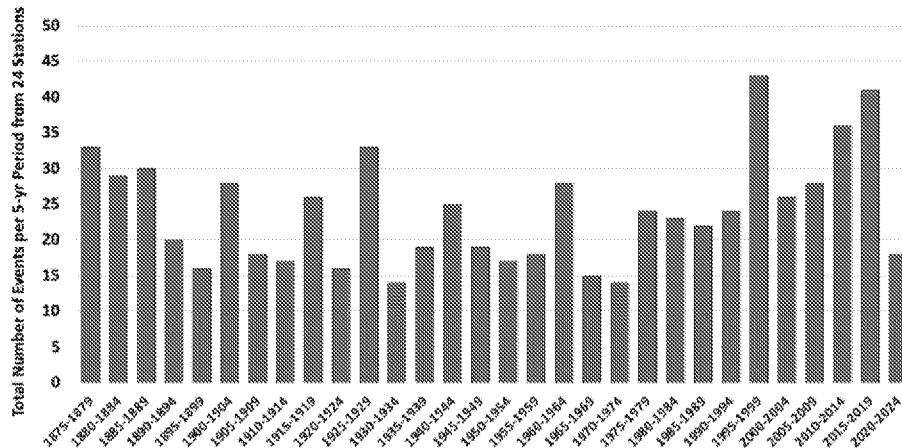
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- Commented [A8R7]:** They're better presented individually esp since we go into additional detail on the NE region
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#### Southeast heavy rainfall events

- The trend in average precipitation is positive and significant in Mobile AL and Quitman GA, and insignificant elsewhere.
- The trend in rainfall variance is positive and significant in Mobile AL, insignificant elsewhere.
- The trend in daily maximum precipitation is positive and significant in Vicksburg MS and Norfolk VA, and insignificant elsewhere.
- Averaged over all stations in the region none of these three trend parameters is statistically significant

Figure 7.5.4 shows the same calculation for the last 150 years in the Southeast humid zone. The temporal pattern of 5-day totals of the 1-in-5yr heavy events is generally unremarkable, though a cluster of higher values appears in 1995 to 2019. The increase in those years is due largely to the 4 northeastern-most stations of Wilmington NC, Weldon NC, Washington DC, and Norfolk VA. This confirms the pattern indicated in NCA4 and NCA5 of a tendency for an increasing frequency of heavy events due to a temporal clustering of tropical storms from eastern NC to Maine discussed below. Otherwise, the remaining 20 stations show an unremarkable temporal distribution of heavy events. The temporal pattern of 5-day totals of the 1-in-5 yr year heavy events in the humid Southeast (Figure 8.7.4.65.2) is generally unremarkable, though a cluster of higher values appears in 1995 to 2019. The increase in those years is due largely to the 4 northeastern-most stations of Wilmington NC, Weldon NC, Washington DC, and Norfolk VA. This confirms the pattern indicated in NCA417 and NCA523 of a tendency for an increasing frequency of heavy events, due to a temporal clustering of tropical

storms from eastern NC to Maine discussed below. Otherwise, the remaining 20 stations show an unremarkable temporal distribution of heavy events.



**Figure 7.5.4.** As in Fig. 7.5.3 but for the heaviest 30 (1-in-5yr) events for 24 stations in the humid Southeast from Austin TX to Washington DC in 5-year bins for 1875-2024.

**Figure 8.7.4.65.3.** As above but for the 30 heaviest 1-in-5yr events for 24 stations in the humid Southeast from Austin TX to Washington DC in 5-year bins for 1875-2024.

#### Northwest heavy rainfall events

- The trend in average precipitation is positive and significant in 9 of 21 locations and in the region averaged overall.
- The trend in rainfall variance is positive and significant in Portland ME, Albany NY and Buffalo NY; insignificant elsewhere.
- The trend in daily maximum precipitation is positive and significant in Portland ME and Gardiner ME; insignificant elsewhere.
- Averaged over all stations in the region the trend parameters for variance and maximum precipitation are not statistically significant.

Fig. 7.5.5 shows the same calculation for the last 135 years in 21 stations in the Northeast (including Montreal Canada). We use 3-day totals here as this produced the largest variations in time. In this region, 72% of the events occur during June to October and are dominated by tropical incursions of hurricanes, tropical storms or tropical storms that transition to extratropical systems. According to NCA17 and NCA23 this region experienced the largest increases in extreme events, so it shall be examined more closely.

Fig. 8.7.4.75.3 shows the 27 (1-in-5yr) heaviest 3-day events for the last 135 years in 21 stations in the Northeast (including Montreal Canada). We use 3-day totals here as this produced the largest variations in time. In this region, 72% of the events occur during June to October and are dominated by tropical incursions of hurricanes, tropical storms or tropical storms that transition to extratropical



systems. According to NCA417 and NCA523 this region experienced the largest increases in extreme events, so it shall be examined more closely.

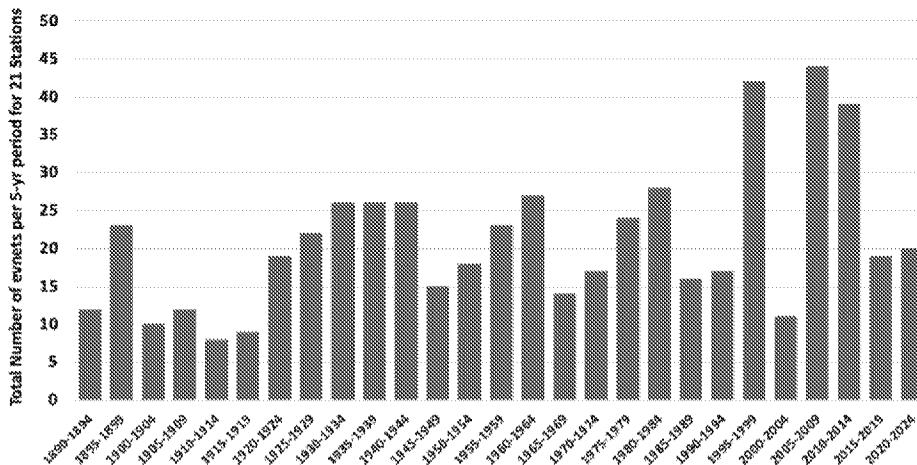


Figure 7.5.5. As in Fig. 7.5.3 but for the heaviest 27 (1-in-5yr) 3-day precipitation events for 21 Northeast stations from NY to ME, including Montreal.

Figure 8.7.4.75.4. Time distribution of the heaviest 27 (1-in-5yr year) heaviest 3-day precipitation events for 21 stations from NY to ME, including Montreal.

There is a noticeable clustering of extreme events from 1995 to 2014. Howarth et al. (2019) examined a similar region as in Fig. 7.5.5 that includes PA and NJ and reported differences between two 18-year periods, 1979-96 and 1997-2014, of various precipitation extremes. They reported a dramatic increase (317%) in 24-hr events exceeding 6 inches. Using the information in Fig. 7.5.5 over the same years we find a 51% increase in the frequency of heavy events. However the frequency drops sharply after 2014, returning to the long-term average over the next decade. It was thus unfortunate that Howarth et al. sample ended in 2014.

Also the high percentage increase in the Howarth et al. sample is associated with small numbers at relatively few locations: there were only 6 in the first period and 25 in the second across 58 stations. Most of the stations did not record such an event. If there is a region-wide increase in heavy events, it should be seen in the average across all stations. Figure 7.5.6 shows the average precipitation in the 1-in-5 yr events across the NE. The trend is only +0.02"/decade. The highest amount, 1935-39, includes the Great New England Hurricane of 1938, one of the rare major (Category 3 or higher) hurricanes to strike the region. The results in Figs. 7.5.5 and 7.5.6 thus suggest that though there was a surge in the number of events at a few locations during the 1995 to 2014 interval, the pattern was not region-wide nor did the change persist after 2014.

Howarth et al. (2019) report differences in the Northeast between two 18-year periods: 1979-96 and 1997-2014 (a similar region as in Fig. 8.7.165.4 that includes PA and NJ) of various precipitation extremes. One metric which indicated a dramatic increase (317%) was found for 24-hr events > 6

inches. This high increase is due to the very small numbers of such events of which there were only 6 in the first period and 25 in the second as reported for 58 stations. This high percentage increase is due to the very small numbers of the events; only 6 in the first period and 25 in the second. Most of the stations did not record such an event suggesting these erratic, episodic events over brief, 18-year periods, need scrutiny by additional statistical methods.

Using the information in Fig. 8.7.4.75.4 over the same years as Howarth et al. we find a 51% increase in the frequency of heavy events between the two periods. One can see in Fig. 8.7.165.4 that it was unfortunate that Howarth et al. ended in 2014, prior to a return to the long-term average of such events.

A feature of Howarth et al. is the use of single day totals, which is questionable because extreme events are often spread across the time-of-observation boundary. Thus stations measuring at 0700 7 am LT local time versus those at Midnight will have differing results for a particular event, which would then have major impacts on counting these events. We use the 3-day totals in Fig. 8.7.4.75.45 to be sure to capture the extent of these extreme downpours. In any case, we can confirm that the period 1997 to 2014 experienced a cluster of heavier events, as Howarth et al. have documented.

Howarth's most remarkable claim (317% increase in 6" days) is potentially misleading because it is a threshold statistic (see Section 8.4.2 8.7.3.2 above) and at the ratio of small numbers over a short period. The result is not representative of *relative* extreme events for the whole region, since the majority of stations never experienced a 6" total. Figure 8.7.165.54 above determines the same number of events for each station (27 heaviest events) whose heaviest values ranged from 4.4" to 12.5" and their 27<sup>th</sup> heaviest values ranged from 3.3" to 5.0". This analysis thus allows each station to be equally represented. In other words, if there is a region-wide increase in heavy events, it should be seen in the sum of all stations. Note too that the period of record here is 135 years vs. 36 years of Howarth et al. Except for three 5-year periods between 1995 and 2014, there is nothing statistically remarkable about the results in Fig. 8.7.4.7.

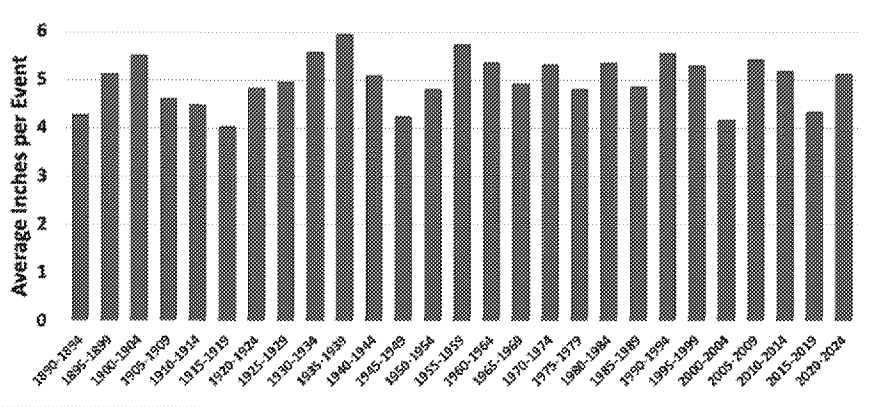


Figure 7.5.6. Average amount of precipitation falling in the 1-in-5yr events for the NE stations.

Figure 8.7.4.85.5. Average amount of precipitation falling in the 1-in-5yr events for the NE stations.

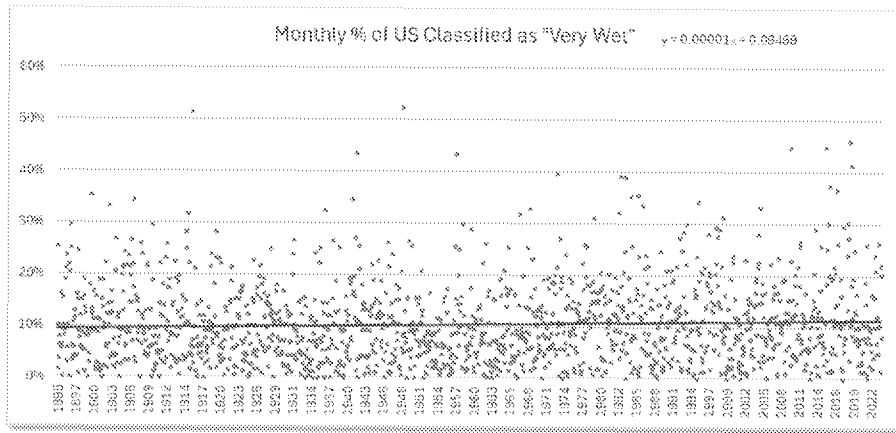
An interesting aspect of Northeast precipitation is that there has been no change in the amount of precipitation per heaviest event, as shown in Fig. 8.7.4.65.5. The trend is only +0.02"/decade. The highest amount, 1935-39, includes the Great New England Hurricane of 1938, one of the rare major (Category 3 or higher) hurricanes to strike the region. The results in Figs. 8.7.4.65.4 and 8.7.4.75.5 suggest that though there was an uptick in the number of events during the period 1995 to 2014, the events, individually, are not becoming more intense.

long et al. (2024) document the increase of tropical influences on precipitation events in the Northeast since 1959 and concluded, "The autumn extreme precipitation trend over the Northeast US is primarily attributed to tropical cyclone-related events since the 1990s." The question then becomes: was the temporal clustering of tropical systems in 1997-2014 which affected the Northeast a response to increasing GHGs (see Chapter 9 Attribution)? long et al. examined CMIP-6 model output which suggests that there will be fewer such systems in the 21<sup>st</sup> century but that the intensity of the rainfall events might increase. This conjecture is not seen in Fig. 8.7.4.75.56 where the amount-per-event has remained steady over the 135-year period.

For substantial urban areas, there is some evidence to indicate the heaviest rainfall events may be redistributed due to the impact urban infrastructure has on the local weather (e.g., Pielke Sr. et al. 2011, Zhang et al. 2018, Yang et al. 2024). Yang et al. state, "Cities that experience compact development tend to witness larger increases in extreme rainfall frequency over downtown than their rural surroundings, while the anomalies in extreme rainfall frequency diminish for cities with dispersed development." While this is an important insight to consider, the effect on the specific stations used in this analysis is unknown, or at least not detectable in Fig. 8.7.4.75.5.

In summary, while apparent increases in extreme precipitation events in some regions over short intervals can be found in the record, the evidence from long term, nationwide historical records does not support the claim that extreme short-duration rainfall events are becoming more frequent or intense.

In summary, the evidence from the historical record of extreme precipitation events in the CONUS is generally not consistent from region to region so that inferences regarding trends and their projections are wrought with significant uncertainty. In most regions and perhaps all, it is our analysis here opinion suggests that given the very nature of the erratic and episodic character of extreme precipitation events, changes that can be confidently categorized as significant relative to natural variability have not been observed renders the discovery of statistically significant changes, including a relationship to CO<sub>2</sub> concentrations, a result yet to be achieved (McKittrick and Christy 2019).



#### 8.7.6 Tornadoes

AR6: [O]bservational trends in tornadoes, hail, and lightning associated with severe convective storms are **not robustly detected** due to insufficient coverage of the long-term observations. There is *medium confidence* that the mean annual number of tornadoes in the USA has remained relatively constant. (Chapter 11, section 11.7.3, p. 1594)

As noted, there is no evidence of trends in US tornadoes or extreme convective storms.

Figure 8.3.84.1: Long-term US wetness (%). Source: NOAA [HYPERLINK "<https://www.ncei.noaa.gov/access/monitoring/uspa/wet-dry/0>"]

#### 8.7.2.27 Flooding

Changes in floods were assessed as follows:

AR6: "The SREX assessed *low confidence* for observed changes in the magnitude or frequency of floods at the global scale. This assessment was confirmed by the AR5 report. The SR15 found increases in flood frequency and extreme streamflow in some regions, but decreases in other regions. . . . [H]ydrological literature on observed flood changes is heterogeneous, focusing at regional and sub-regional basin scales, making it difficult to synthesise at the global and sometimes regional scales." (Chapter 11.5)

AR6: "[T]he seasonality of floods has changed in cold regions where snowmelt dominates the flow regime in response to warming (*high confidence*). Confidence about peak flow trends over past decades on the global scale is *low*." (Chapter 11.5)

NCA 17: "Trends in extreme high values of streamflow are **mixed** across the United States. Analysis of 200 U.S. stream gauges indicates areas of both increasing and decreasing flooding magnitude but does not provide robust evidence that these trends are attributable to human influences" (pp. 240-241)

The absence of detectable US-wide trends in flooding is consistent with the findings in the previous section of absence of coherent changes in extreme precipitation.

SREX (p. 176)

~~In the United States and Canada during the 20th century and in the early 21st century, there is no compelling evidence for climate-driven changes in the magnitude or frequency of floods.~~

AR5 (p. 214)

~~AR4 WGI Chapter 3 (Trenberth et al., 2007) did not assess changes in floods but AR4 WGIH concluded that **there was not a general global trend in the incidence of floods** (Kundzewicz et al., 2007). SREX went further to suggest that there was low agreement and thus *low confidence* at the global scale regarding changes in the magnitude or frequency of floods or even the sign of changes.~~

~~AR5 WGIH assesses floods in regional detail accounting for the fact that trends in floods are strongly influenced by changes in river management (see also Section 2.5.2). Although the most evident flood trends appear to be in northern high latitudes, where observed warming trends have been largest, in some regions no evidence of a trend in extreme flooding has been found, for example, over Russia based on daily river discharge (Shkldomanov et al., 2007). Other studies for Europe (Hannafor and Marsh, 2008; Renard et al., 2008; Petrow and Merz, 2009; Stahl et al., 2010) and Asia (Jiang et al., 2008; Delgado et al., 2010) show evidence for upward, downward or no trend in the magnitude and frequency of floods, so that there is currently no clear and widespread evidence for observed changes in flooding except for the earlier spring flow in snow-dominated regions (Seneviratne et al., 2012). In summary, **there continues to be a lack of evidence and thus *low confidence* regarding the sign of trend in the magnitude and/or frequency of floods on a global scale.**~~

AR6 (Ch. 11 p. 1568)

~~The SREX (Seneviratne et al., 2012) assessed *low confidence* for observed changes in the magnitude or frequency of floods at the global scale. This assessment was confirmed by the AR5 report (Hartmann et al., 2013). The SR15 (Hoegh-Guldberg et al., 2018) found increases in flood frequency and extreme streamflow in some regions, but decreases in other regions. **While the number of studies on flood trends has increased since the AR5 report, and**~~

there were also new analyses after the release of SR15 (Berghuijs et al., 2017; Blöschl et al., 2019; Gudmundsson et al., 2019); hydrological literature on observed flood changes is heterogeneous, focusing at regional and sub-regional basin scales, making it difficult to synthesise at the global and sometimes regional scales.

In summary, the seasonality of floods has changed in cold regions where snow melt dominates the flow regime in response to warming (high confidence). Confidence about peak flow trends over past decades on the global scale is low, but there are regions experiencing increases, including parts of Asia, southern South America, the northeast USA, northwestern Europe, and the Amazon, and regions experiencing decreases, including parts of the Mediterranean, Australia, Africa, and the southwestern USA.

US-NCA17, pp. 240-41:

"The IPCC AR5 did not attribute changes in flooding to anthropogenic influence nor report detectable changes in flooding magnitude, duration, or frequency. Trends in extreme high values of streamflow are mixed across the United States. Analysis of 200 U.S. stream gauges indicates areas of both increasing and decreasing flooding magnitude but does not provide robust evidence that these trends are attributable to human influences...

The complex mix of processes complicates the formal attribution of observed flooding trends to anthropogenic climate change and suggests that additional scientific rigor is needed in flood attribution studies. As noted above, precipitation increases have been found to strongly influence changes in flood statistics. However, in U.S. regions, no formal attribution of precipitation changes to anthropogenic forcing has been made so far, so indirect attribution of flooding changes is not possible. Hence, no formal attribution of observed flooding changes to anthropogenic forcing has been claimed."

### 8.2.3 Heatwaves

AR5 (p. 212 WG1)

Table 2.13 shows that there has been a likely increasing trend in the frequency of heatwaves since the middle of the 20th century in Europe and Australia and across much of Asia where there are sufficient data. However, confidence on a global scale is medium owing to lack of studies over Africa and South America but also in part owing to differences in trends depending on how heatwaves are defined (Perkins et al., 2013). Using monthly means as a proxy for heatwaves Coumou et al. (2013) and Hansen et al. (2012) indicate that record-breaking temperatures in recent decades substantially exceed what would be expected by chance but caution is required when making inferences between these studies and those that deal with multi-day events and/or use more complex definitions for heatwave events. There is also evidence in some regions that periods prior to the 1950s had more heatwaves (e.g., over the USA, the decade of the 1930s stands out and is also associated with extreme drought conditions (Peterson et al., 2013) whereas conversely in other regions heatwave trends may have been underestimated owing to poor quality and/or consistency of data (e.g., Della-Marta et al. (2007a) over Western Europe; Kuglitsch et al. (2009, 2010) over the Mediterranean). Recent available studies also suggest that the number of cold spells has reduced significantly since the 1950s (Donat et al., 2013a, 2013c).

In summary, new analyses continue to support the AR4 and SREX conclusions that since about 1950 it is very likely that the numbers of cold days and nights have decreased and the

numbers of warm days and nights have increased overall on the global scale, that is, for land areas with sufficient data. It is *likely* that such changes have also occurred across most of North America, Europe, Asia and Australia.

NCA17 (pp. 190-191)

Changes in warm extremes are more nuanced than changes in cold extremes. For instance, **the warmest daily temperature of the year increased in some parts of the West over the past century (Figure 6.3), but there were decreases in almost all locations east of the Rocky Mountains. In fact, all eastern regions experienced a net decrease (Table 6.2),** most notably the Midwest (about 2.2°F [1.2°C]) and the Southeast (roughly 1.5°F [0.8°C]). The decreases in the eastern half of [the] Nation, particularly in the Great Plains, are mainly tied to the unprecedented summer heat of the 1930s Dust Bowl era, which was exacerbated by land surface feedbacks driven by springtime precipitation deficits and land mismanagement. However, anthropogenic aerosol forcing may also have reduced summer temperatures in the Northeast and Southeast from the early 1950s to the mid-1970s, and agricultural intensification may have suppressed the hottest extremes in the Midwest.

Since the mid-1960s, there has been only a very slight increase in the warmest daily temperature of the year (amidst large interannual variability). **Heat waves (6-day periods with a maximum temperature above the 90th percentile for 1961–1990) increased in frequency until the mid-1930s, became considerably less common through the mid-1960s, and increased in frequency again thereafter (Figure 6.4).** As with warm daily temperatures, heat wave magnitude reached a maximum in the 1930s.

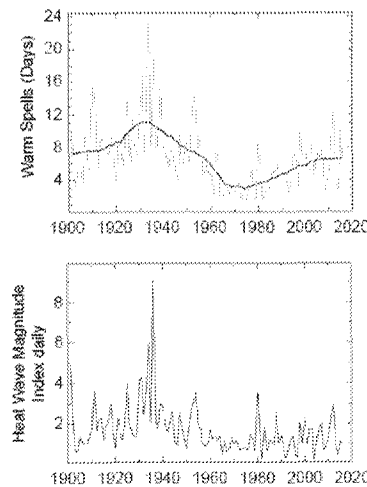


Figure 8.2.1: US Heat waves since 1900. Source: NCA17 Figure 6.4

AR6 (p. 1550)

In North America (Table 11.19), there is very robust evidence for a *very likely* increase in the intensity and frequency of hot extremes and decrease in the intensity and frequency of cold

extremes for the whole continent, though there are substantial spatial and seasonal variations in the trends. Minimum temperatures display warming consistently across the continent, while there are more contrasting trends in the annual maximum daily temperatures in parts of the USA (Figure 11.9; Lee et al., 2014; van Oldenborgh et al., 2019; Dunn et al., 2020).

#### 8.2.4 Extreme snowfall events

Note: extreme snowfall events in the US northeast are assessed in relation to winter Extratropical Cyclone (ETC) activity.

AR6 Ch 11, p. 1593

There is *high confidence* that snowfall associated with winter ETCs will decrease in the future, because increases in tropospheric temperatures lead to a lower proportion of precipitation falling as snow (O’Gorman, 2014; Rhoades et al., 2018; Zarzycki, 2018). However, there is *medium confidence* that extreme snowfall events associated with winter ETCs will change little in regions where snowfall will be supported in the future (O’Gorman, 2014; Zarzycki, 2018).

#### 8.2.5 Extreme precipitation

SREX (p. 142)

Recent studies have updated the assessment of the AR4, with more regional results now available (Table 3-2). Overall, this additional evidence confirms that **more locations and studies show an increase than a decrease in extreme precipitation, but that there are also wide regional and seasonal variations**, and trends in many regions are not statistically significant (Table 3-2). Based on station data from Canada, the United States, and Mexico, Peterson et al. (2008a) reported that heavy precipitation has been increasing over 1950–2004, as well as the average amount of precipitation falling on days with precipitation.

AR5 (pp. 213–14)

In summary, further analyses continue to support the AR4 and SREX conclusions that **it is likely that since 1951 there have been statistically significant increases in the number of heavy precipitation events (e.g., above the 95th percentile) in more regions than there have been statistically significant decreases, but there are strong regional and subregional variations in the trends**. In particular, many regions present statistically non-significant or negative trends, and, where seasonal changes have been assessed, there are also variations between seasons (e.g., more consistent trends in winter than in summer in Europe). The overall most consistent trends towards heavier precipitation events are found in central North America (very likely increase) but assessment for Europe shows likely increases in more regions than decreases.

AR6 (p. 1560)

In North America, there is robust evidence that the magnitude and intensity of extreme precipitation has *very likely* increased since the 1950s. Both [one-day maximal] and [5-day maximal] have significantly increased in North America during 1950–2018 (Sun et al., 2020, also Figure 11.13). There is, however, regional diversity: in Canada, there is a lack of



detectable trends in observed annual maximum daily (or shorter duration) precipitation (Shephard et al., 2014; Mekis et al., 2015; Vincent et al., 2018).

NCA17, pp. 213-14:

Detectability of trends (compared to internal variability) for a number of precipitation metrics over the continental United States has been examined; however, trends identified for the U.S. regions have not been clearly attributed to anthropogenic forcing. One study concluded that increasing precipitation trends in some north-central U.S. regions and the extreme annual anomalies there in 2013 were at least partly attributable to the combination of anthropogenic and natural forcing. Based on current evidence, it is concluded that detectable but not attributable increases in mean precipitation have occurred over parts of the central United States. Formal detection-attribution studies indicate a human contribution to extreme precipitation increases over the continental United States, but confidence is low based on those studies alone due to the short observational period, high natural variability, and model uncertainty.

In summary, based on available studies, it is concluded that for the continental United States there is high confidence in the detection of extreme precipitation increases, while there is low confidence in attributing the extreme precipitation changes purely to anthropogenic forcing.

#### **8.2.6 Tornadoes and severe convective storms**

IPCC AR6 Sct. 11.7.3, p. 1594

Severe convective storms are convective systems that are associated with extreme phenomena such as tornadoes, hail, heavy precipitation (rain or snow), strong winds, and lightning.

The assessment of changes in severe convective storms in SREX (Chapter 3, Seneviratne et al., 2012) and AR5 (Chapter 12, Collins et al., 2013) is limited and focused mainly on tornadoes and hail storms. The SREX assessed that there is low confidence in observed trends in tornadoes and hail because of data inhomogeneities and inadequacies in monitoring systems. Subsequent literature assessed in the Climate Science Special Report (Kossin et al., 2017) led to the assessment of the observed tornado activity over the 2000s in the USA, with a decrease in the number of days per year with tornadoes and an increase in the number of tornadoes on these days (medium confidence). However, there is low confidence in past trends for hail and severe thunderstorm winds. Climate models consistently project environmental changes that would support an increase in the frequency and intensity of severe thunderstorms that combine tornadoes, hail, and winds (high confidence), but there is low confidence in the details of the projected increase.

... In summary, because the definition of severe convective storms varies depending on the literature and the region, it is not straightforward to make a synthesizing view of observed trends in severe convective storms in different regions. In particular, observational trends in tornadoes, hail, and lightning associated with severe convective storms are not robustly detected due to insufficient coverage of the long-term observations. There is medium confidence that the mean annual number of tornadoes in the USA has remained relatively constant, but their variability of occurrence has increased since the 1970s, particularly over the 2000s, with a decrease in the number of days per year, and an increase in the number

of tornadoes on these days (*high confidence*). Detected tornadoes have also increased in Europe, but the trend depends on the density of observations.

In summary, it is extremely difficult to detect and attribute changes in severe convective storms. There is limited evidence that extreme precipitation associated with severe convective storms has increased in some cases.

## 8.2.7 Hurricanes and Tropical Cyclones

SREX (p. 159):

There have been no significant trends observed in global tropical cyclone frequency records, including over the present 40-year period of satellite observations (e.g., Webster et al., 2000). Regional trends in tropical cyclone frequency have been identified in the North Atlantic, but the fidelity of these trends is debated (Holland and Webster, 2007; Landsea, 2007; Mann et al., 2007a). Different methods for estimating undercounts in the earlier part of the North Atlantic tropical cyclone record provide mixed conclusions (Chang and Guo, 2007; Mann et al., 2007b; Kunkel et al., 2008; Vecchi and Knutson, 2009). Regional trends have not been detected in other oceans (Chan and Xu, 2009; Kubota and Chan, 2009; Callaghan and Power, 2011). It thus remains uncertain whether any observed increases in tropical cyclone frequency on time scales longer than about 40 years are robust after accounting for past changes in observing capabilities (Knutson et al., 2010).

AR5 (pp. 216–17):

Current data sets indicate no significant observed trends in global tropical cyclone frequency over the past century and it remains uncertain whether any reported long-term increases in tropical cyclone frequency are robust after accounting for past changes in observing capabilities (Knutson et al., 2010). No robust trends in annual numbers of tropical storms, hurricanes and major hurricanes counts have been identified over the past 100 years in the North Atlantic basin. Measures of land-falling tropical cyclone frequency (Figure 2.34) are generally considered to be more reliable than counts of all storms which tend to be strongly influenced by those that are weak and/or short-lived. Callaghan and Power (2011) find a statistically significant decrease in Eastern Australia land-falling tropical cyclones since the late 19th century although including 2010/2011 season data this trend becomes non-significant (i.e., a trend of zero lies just inside the 90% confidence interval). Significant trends are not found in other oceans on shorter time scales (Chan and Xu, 2009; Kubota and Chan, 2009; Mohapatra et al., 2011; Weinkle et al., 2012), although Grinsted et al. (2012) find a significant positive trend in eastern USA using tide gauge data from 1923–2008 as a proxy for storm surges associated with land-falling hurricanes. Differences between tropical cyclone studies highlight the challenges that still lie ahead in assessing long-term trends.

In summary, this assessment does not revise the SREX conclusion of low confidence that any reported long-term (centennial) increases in tropical cyclone activity are robust, after accounting for past changes in observing capabilities. More recent assessments indicate that it is unlikely that annual numbers of tropical storms, hurricanes and major hurricanes counts have increased over the past 100 years in the North Atlantic basin. Evidence, however, is for a virtually certain increase in the frequency and intensity of the strongest tropical cyclones since the 1970s in that region.

AR6 (p. 1525)

~~There is low confidence in most reported long-term (multidecadal to centennial) trends in TC frequency or intensity based metrics due to changes in the technology used to collect the best track data. This should not be interpreted as implying that no physical (real) trends exist, but rather as indicating that either the quality or the temporal length of the data is not adequate to provide robust trend detection statements, particularly in the presence of multidecadal variability.~~

~~There are previous and ongoing efforts to homogenize the best track data (Elsner et al., 2008; Kossin et al., 2013, 2020; Choy et al., 2015; Landsea, 2015; Emanuel et al., 2018) and there is substantial literature that finds positive trends in intensity-related metrics in the best track during the "satellite period" which is generally limited to the past ~40 years (Kang and Elsner, 2012; Kishitani et al., 2013; Kossin et al., 2013, 2020; Mai and Xie, 2016; Zhao et al., 2018; Tawale and Truboki, 2019). When best track trends are tested using homogenized data, the intensity trends generally remain positive, but are smaller in amplitude (Kossin et al., 2013; Holland and Bruyere, 2014). Kossin et al. (2020) extended the homogenized TC intensity record to the period 1979–2017 and identified significant global increases in major TC exceedance probability of about 6% per decade. In addition to trends in TC intensity, there is evidence that TC intensification rates and the frequency of rapid intensification events have increased within the satellite era (Kishitani et al., 2013; Balaguru et al., 2018; Bhatia et al., 2018). The increase in intensification rates is found in the best track as well as the homogenized intensity data.~~

~~A subset of the best track data corresponding to hurricanes that have directly impacted the United States since 1900 is considered to be reliable, and shows no trend in the frequency of U.S. landfall events (Knutson et al., 2019).~~

### 8.7.2.868 Droughts

Assessments of drought trends were as follows.

AR6: "Few AR6 regions show observed increases in meteorological drought" (Section 11.9, p. 1575).

~~<sup>4</sup>The underlined text referenced a study (Kossin et al. 2020) that later retracted a portion of its findings. Those authors assembled a data set on global TC incidence spanning 1979 to 2017 from which they claimed that the global fraction of TCs reaching major status (Cat 3–5) rose from 27% during 1979–1997 to 31% during 1998–2017 and that the increase was statistically significant. However, closer examination of their results showed a significant increase only in the North Atlantic (18% to 34%) whereas changes in all other basins (Eastern Pacific, Western Pacific, North Indian, South Indian, South Pacific) were not statistically significant. In a subsequent correction ([HYPERLINK "https://www.pnas.org/doi/10.1073/pnas.2021573117"]), Kossin et al. stated that the global probability of observing a major TC rose from 34% during 1979–1997 to 37% in the later period and that the evidence for statistical significance was now weaker. Nevertheless, the authors claimed that the correction did not affect their conclusions.~~

AR6: "Increasing trends in agricultural and ecological droughts have been observed on all continents (*medium confidence*), but decreases only in one AR6 region (*medium confidence*). Increasing trends in hydrological droughts have been observed in a few AR6 regions." (Chapter 11 Summary)

NCA17: "As a consequence of this increased precipitation, drought statistics over the entire CONUS have **declined**." (p. 233)

NCA17: "Recent droughts and associated heat waves have reached record intensity in some regions of the United States; however, by geographical scale and duration, the Dust Bowl era of the 1930s **remains the benchmark** drought and extreme heat event in the historical record (very high confidence)." (p. 231)

SREX: "From a paleoclimate perspective, recent droughts are **not unprecedented**, with severe 'megadroughts' reported in the paleoclimatic record for Europe, North America, and Australia." (p. 170)

US NCA17 REPORT (Ch. 8, Wehner et al. 2017)

p. 231:

~~Recent droughts and associated heat waves have reached record intensity in some regions of the United States; however, by geographical scale and duration, the Dust Bowl era of the 1930s remains the benchmark drought and extreme heat event in the historical record (very high confidence). While by some measures drought has decreased over much of the continental United States in association with long-term increases in precipitation, neither the precipitation increases nor inferred drought decreases have been confidently attributed to anthropogenic forcing.~~

~~The human effect on recent major U.S. droughts is complicated. Little evidence is found for a human influence on observed precipitation deficits, but much evidence is found for a human influence on surface soil moisture deficits due to increased evapotranspiration caused by higher temperatures. (*High confidence*)~~

p. 233:

~~Drought is, of course, directly connected to seasonal precipitation totals. Figure 7.1 shows detectable observed recent changes in seasonal precipitation. In fact, the increases in observed summer and fall precipitation are at odds with the projections in Figure 7.5. As a consequence of this increased precipitation, drought statistics over the entire CONUS have declined.~~

SREX (p. 170)

~~From a paleoclimate perspective recent droughts are not unprecedented, with severe 'megadroughts' reported in the paleoclimatic record for Europe, North America, and Australia (Jansen et al., 2007). Recent studies extend this observation to African and Indian droughts (Sinha et al., 2007; Shanahan et al., 2009); much more severe and longer droughts occurred in the past centuries with widespread ecological, political, and socioeconomic consequences. Overall, these studies confirm that in the last millennium several extreme droughts have occurred (Breda and Badeau, 2008; Kallis, 2008; Büntgen et al., 2010).~~

~~In North America, there is *medium confidence* that there has been an overall slight tendency toward less dryness (wetting trend with more soil moisture and runoff; Table 3-~~

2), although analyses for some subregions also indicate tendencies toward increasing dryness. This assessment is based on several lines of evidence, including simulations with different hydrological models as well as PDSI and CDD estimates (Alexander et al., 2006; Andreadis and Lettenmaier, 2006; van der Schrier et al., 2006a; Kunkel et al., 2008; Sheffield and Wood, 2008a; Dai, 2011).

The most severe droughts in the 20th century have occurred in the 1930s and 1950s, where the 1930s Dust Bowl was most intense and the 1950s drought most persistent (Andreadis et al., 2005) in the United States, while in Mexico the 1950s and late 1990s were the driest periods. Recent regional trends toward more severe drought conditions were identified over southern and western Canada, Alaska, and Mexico, with subregional exceptions (Dai, 2011).

SREX (p. 172)

Overall, though new studies have furthered the understanding of the mechanisms leading to drought, there is still relatively limited evidence to provide an attribution of observed changes, in particular given the issues associated with the availability of observational data (Section 3.2.1) and the definition and computation of drought indicators (Box 3-3). This latter point was mostly identified in post-AR4 studies (Box 3-3). Moreover, regions where consistent increases in drought are identified (see 'Observed Changes') are only partly consistent with those where projections indicate an enhancement of drought conditions in coming decades (see next paragraphs). We thus assess that there is *medium confidence* (see also Section 3.1.5) that anthropogenic influence has contributed to some changes in the drought patterns observed in the second half of the 20<sup>th</sup> century, based on its attributed impact on precipitation and temperature changes (though temperature can only be indirectly related to drought trends; see Box 3-3). However, there is *low confidence* in the attribution of changes in droughts at the level of individual regions.

AR5 (pp. 214-215)

Based on evidence since AR4, SREX concluded that there were not enough direct observations of dryness to suggest high confidence in observed trends globally, although there was *medium confidence* that since the 1950s some regions of the world have experienced more intense and longer droughts. The differences between AR4 and SREX are due primarily to analyses post-AR4, differences in how both assessments considered drought and updated IPCC uncertainty guidance.

Because drought is a complex variable and can at best be incompletely represented by commonly used drought indices, discrepancies in the interpretation of changes can result. For example, Sheffield and Wood (2008) found decreasing trends in the duration, intensity and severity of drought globally. Conversely, Dai (2011a,b) found a general global increase in drought, although with substantial regional variation and individual events dominating trend signatures in some regions (e.g., the 1970s prolonged Sahel drought and the 1930s drought in the USA and Canadian Prairies). Studies subsequent to these continue to provide somewhat different conclusions on trends in global droughts and/or dryness since the middle of the 20th century (Sheffield et al., 2012; Dai, 2013; Donat et al., 2013c; van der Schrier et al., 2013).

In summary, the current assessment concludes that there is not enough evidence at present to suggest more than *low confidence* in a global-scale observed trend in drought or dryness (lack of rainfall) since the middle of the 20th century, owing to lack of direct observations, geographical inconsistencies in the trends, and dependencies of

inferred trends on the index choice. Based on updated studies, AR4 conclusions regarding global increasing trends in drought since the 1970s were probably overstated. However, it is likely that the frequency and intensity of drought has increased in the Mediterranean and West Africa and decreased in central North America and north-west Australia since 1950.

AR6 (Drought, Observed trends, Section 11.6.2, pp. 1573-75)

p. 1573

Strong precipitation deficits have been recorded in recent decades in the Amazon (2005–2010), south-western China (2009–2010), south-western North America (2011–2014), Australia (1997–2009), California (2014), the middle East (2012–2016), Chile (2010–2015), the Great Horn of Africa (2011), among others (van Dijk et al., 2013; Mann and Gleick, 2015; Rowell et al., 2015; Marengo and Espinoza, 2016; Dai and Zhao, 2017; Garreaud et al., 2017, 2020; Marengo et al., 2017; Brito et al., 2018; Cook et al., 2018). **Global studies generally show no significant trends in SPI time series** (Orlowsky and Seneviratne, 2013; Spinoni et al., 2014), **and in derived drought frequency and severity data** (Spinoni et al., 2019), with very few regional exceptions (Section 11.9 and Figure 11.17).

p. 1574

For AR6 regions, several studies suggest an increase in the frequency and areal extent of soil moisture deficits, with examples in East Asia (Cheng et al., 2015; Y. Qin et al., 2015; Jia et al., 2018), Western and Central Europe (Trnka et al., 2015b), and the Mediterranean (Hanel et al., 2018; Moravec et al., 2019; Markonis et al., 2021). **Nonetheless, some analyses also show no long-term trends in soil drying in some AR6 regions – for example, in Eastern North America (Park Williams et al., 2017) and Central North America (Seager et al., 2019), as well as in North Eastern Africa (Kew et al., 2021).**

There is evidence based on streamflow records of increased hydrological droughts in East Asia (D. Zhang et al., 2018) and southern Africa (Gudmundsson et al., 2019). **In areas of Western and Central Europe and Northern Europe, there is no evidence of changes in the severity of hydrological droughts since 1950** based on flow reconstructions (Caillaud et al., 2017; Barker et al., 2019) and observations (Vicente-Serrano et al., 2019). **In North America, depending on the methods, datasets and study periods, there are differences between studies that suggest an increase (Shukla et al., 2015; Udall and Overpeck, 2017) versus a decrease in hydrological drought frequency (Mo and Lettenmaier, 2018), but in general there is strong spatial variability** (Poshtiri and Pal, 2016). Streamflow observation reference networks of near-natural catchments have also been used to isolate the effect of climate trends on hydrological drought trends in a few regions, but these show limited trends in Northern Europe and Western and Central Europe (Stahl et al., 2010; Bard et al., 2015; Harrigan et al., 2018), North America (Dudley et al., 2020), and most of Australia, with the exception of Eastern and Southern Australia (X.S. Zhang et al., 2016).

p. 1575

**Few AR6 regions show observed increases in meteorological drought** (Section 11.9), mostly in Africa and South America (NES: *high confidence*; WAF, CAF, ESAF, SAM, SWS, SSA, SAS: *medium confidence*); a few others show a decrease (WSB, ESB, NAU, CAU, NEU, CNA: *medium confidence*). There are stronger signals indicating observed increases in agricultural and ecological drought (Section 11.9), which highlights the role of increased [evapotranspiration], driven by increased [Atmospheric Evaporative Demand], for these

trends (Sections 11.6.2.3, 11.6.2.5). Past increases in agricultural and ecological droughts are found on all continents and several regions (WAF, CAF, WSAF, ESAF, WCA, ECA, EAS, SAU, MED, WCE, NES; medium confidence), while decreases are found only in one AR6 region (NAU; medium confidence). The more limited availability of datasets makes it more difficult to assess historical trends in hydrological drought at regional scale (Section 11.9). Increasing (MED; high confidence; WAF, EAS, SAU; medium confidence) and decreasing (NEU, SES; medium confidence) trends in hydrological droughts have only been observed in a few regions.

#### AR6 on Attribution (p. 1577)

There are only two AR6 regions in which there is at least *medium confidence* that human-induced climate change has contributed to changes in meteorological droughts (Section 11.9). In South-western South America (SSW), there is *medium confidence* that human-induced climate change has contributed to an increase in meteorological droughts (Boisier et al., 2016; Garreaud et al., 2020), while in Northern Europe (NEU), there is *medium confidence* that it has contributed to a decrease in meteorological droughts (Gudmundsson and Seneviratne, 2016) (Section 11.9). In other AR6 regions, there is *inconclusive evidence in the attribution of long-term trends, but a human contribution to single meteorological events or subregional trends has been identified in some instances*. In North America, the human influence on precipitation deficits is complex (Wehner et al., 2017), with *low confidence in the attribution of long-term changes in meteorological drought in AR6 regions*.

As shown in Figure 8.7.3.968.1, US long term data (NOAA) shows an insignificantly declining tendency toward extreme dryness (-0.0001% per year)

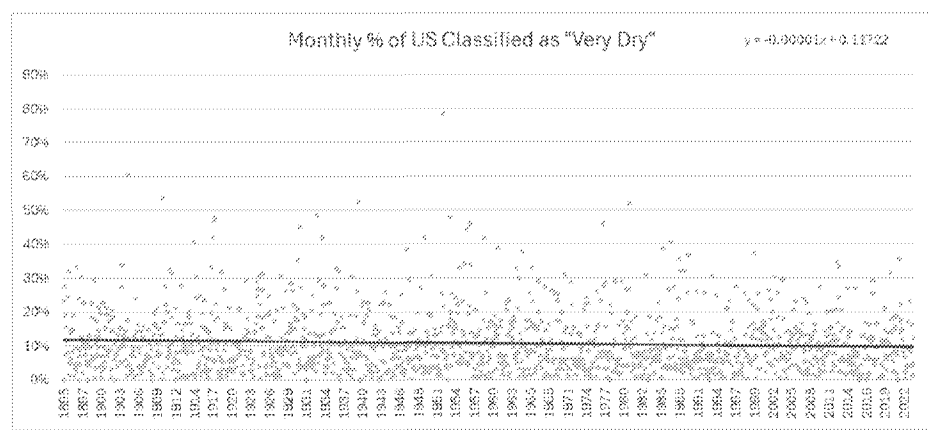


Figure 8.7.3.968.1: US dryness (%) 1895–2023. Source: NOAA [HYPERLINK "<https://www.ncei.noaa.gov/access/monitoring/uspa/wet-dry/0>"]

Kogan et al. (2020) examines a 38-year high-resolution satellite-based drought measure and concludes that global drought has not intensified and is not connected to climate change: "it is possible to state firmly that global and main grain countries' drought area and intensity trends have not been following global climate warmings since 1980's."

### 8.32 Extreme weather trends at global and continental indicators of scale extreme weather trends

#### 8.32.1 Tropical Cyclones (TCs)

Hurricane strength records for the North Atlantic and the Western Pacific go back to 1950 and the record does not show an increase in either total or major TCs. Figure 8.3.1 was published by Roger Pielke Jr. as an update to the Best Track data series originally presented in Weinkle et al. (2012).

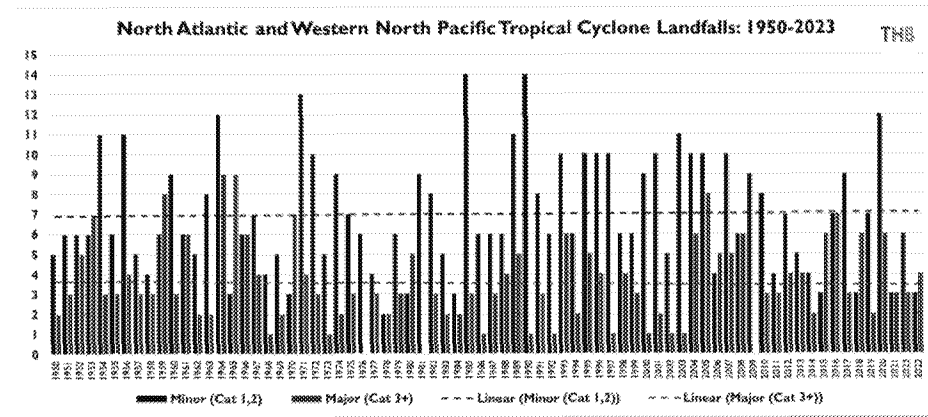


Figure 8.3.1. Tropical Cyclone Landfalls. Source: [HYPERLINK "https://rogerpielkejr.substack.com/p/global-tropical-cyclones"]-Weinkle et al. (2012)

Similarly, [After 1980, as shown in Figure 8.3.2, ]Maue 2025, [HYPERLINK "https://climatlas.com/tropical/"] shows that which reproduces data from the Climate Atlas of Dr. Ryan Maue both neither all hurricanes and the total number of hurricanes nor the frequency of major ones hurricanes have not become more common since 1980, the period of rapidly growing human influences. In fact, deed both numbers have trended down slightly since the 1990s:

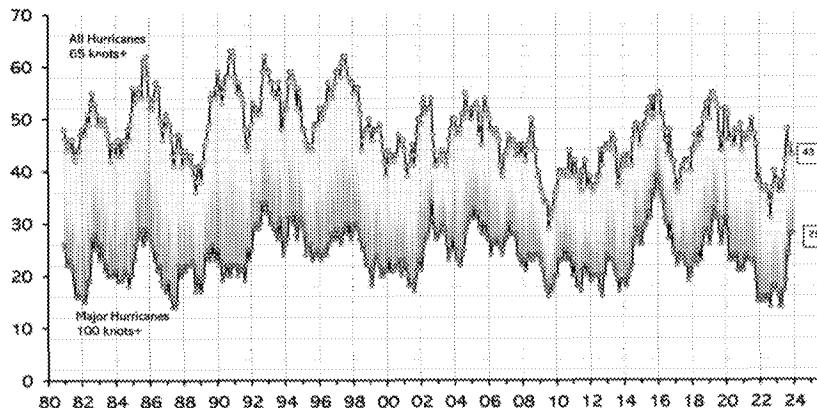
Commented [A12]: I find the Climate Atlas of Dr. Ryan Maue



Global Major Hurricane Frequency – 12 month running sums – @RyanMaue

Updated December 31, 2023

Last 30-years: 45.7 H | 24.4 M



Global Major Hurricane Frequency – 12 month running sums – @RyanMaue

Updated March 10, 2025

Last 30-years, annual: 45 H | 24 M

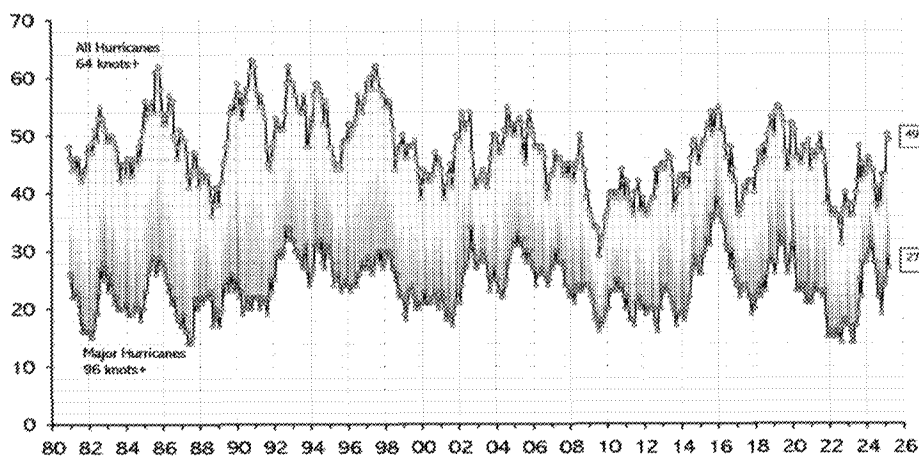
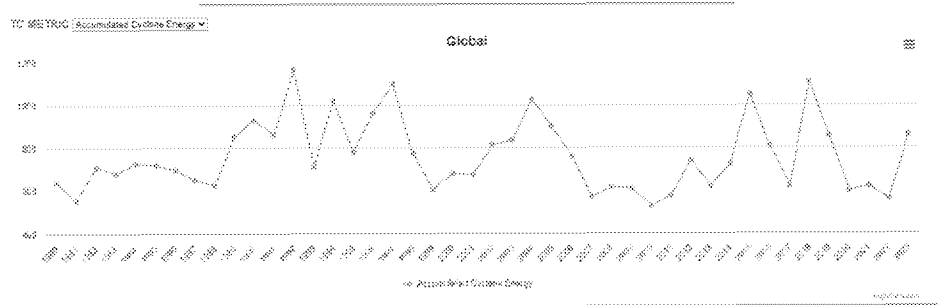


Figure 8.3.2: Global hurricane frequency. Source: Maue (2024/2025)

A metric that combines the number, duration, and frequency strength of TCs is the Accumulated Cyclone Energy (or ACE) Index maintained at Colorado State University, shown in Figure 8.3.3. As is clear, it is also not clearly shows no long-term increase, in fact declining slightly and since 1990 has declined slightly.



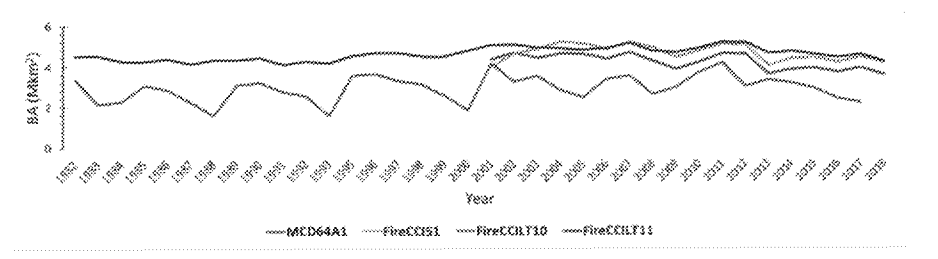
**Figure 8.3.3: Global Accumulated Cyclone Energy.** Source: Klotzbach (2025)  
 [HYPERLINK "<https://tropical.atmos.colostate.edu/Realtime/index.php?arch&loc=global>"]

Note that Tu et al. (2024) report that the Power Dissipation Index (PDI), another different measure of the destructiveness of hurricanes that combines hurricane number, duration, and strength, has either remained unchanged or has declined in all global oceanic basins since the mid-1990s. As is clear, it is also not increasing and since 1990 has declined slightly.

Today's global climate simulations are too coarse to project changes in TCs directly. Rather, projections are derived from finer "downscaled" simulations or proxies involving sea surface temperatures, winds, and aerosols. By these methods, a warming climate is expected to show climate models project declining hurricane formation rates in a warming climate (Chand et al. 2022). Climate models also project fewer Tropical Cyclones under future global warming, and even though models project they will increase in strength, the annual averages of rainfall maxima decline (Stansfield et al. 2020). Note that Tu et al. (2024) report that the Power Dissipation Index (PDI), a measure of the destructiveness of hurricanes, has either remained unchanged or has declined in all global oceanic basins since the mid-1990s.

### 8.7.23.279 Wildfires

The IPCC has not provided an assessment of wildfires. As shown in Figures 8.7.3.479.1 and 8.3.5 global wildfire activity as measured by European Space Agency peaked over a decade ago and shows a downward trend since this in the 21<sup>st</sup> century.

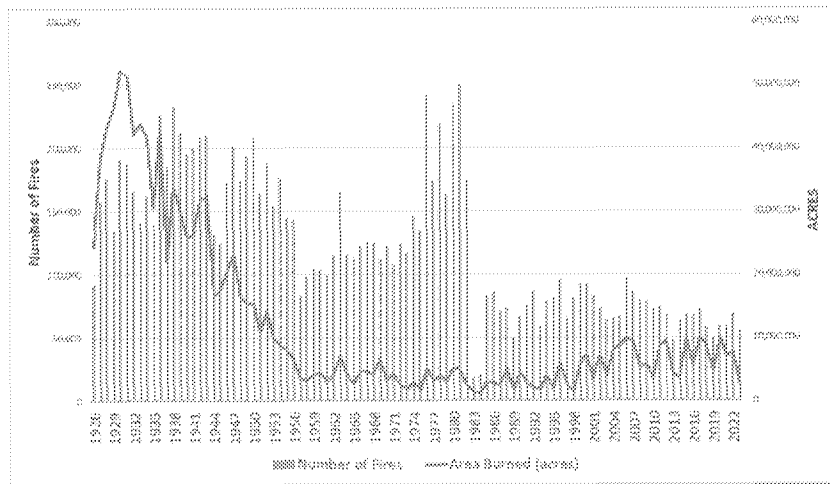


**Figure 8.3.4:** Global wildfire 1982-2018. Source: Copied from Oton et al. (2021). Note: the different coloured lines represent different data products based on satellites and algorithms used.



**Figure 8.7.3.579.1:** Global wildfire 2001-2018. Source: Copied from Lizundia-Loiola et al. (2021). Note: the different coloured lines represent different data products based on satellites and algorithms used.

US data from the National Interagency Fire Centre (NIFC) from 1926 to 2023 are shown in Figure 8.3.679.2.



**Figure 7.9.2:** US wildfires 1926 to 2023. Source: Post-2018: National InterAgency Fire Centre data Pre-2017 [webarchive.org](https://www.webarchive.org).

**Figure 8.7.3.679.2:** US wildfires 1926 to 2023. Source: National InterAgency Fire Centre data Pre-2017 (archived)

**Commented [A12]:** I thought the trends were due to declining fires in the Amazon, masking any climate-related trend?

**Commented [A13R12]:** "global area burned appears to have overall declined over past decades, and there is increasing evidence that there is less fire in the global landscape today than centuries ago." Doerr and Santin, Proc Royal Society 2016

[HYPERLINK

"file:///C:/Users/Porter%20Hill/Dropbox/Brucehaven/Projects/DoE/Ross%20drafts/Pre-

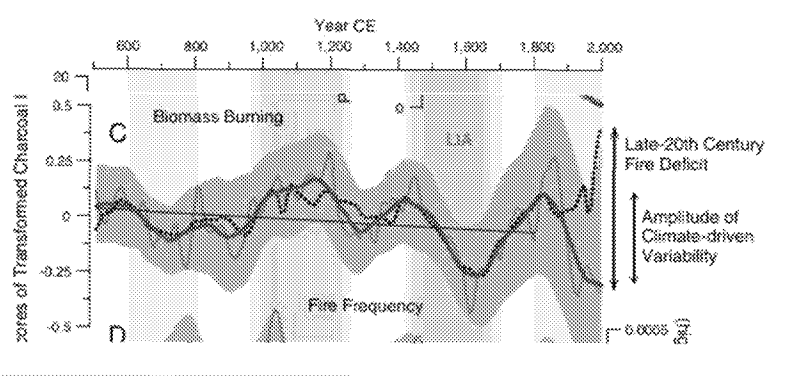
2017):%20https://web.archive.org/web/20200212033452/https://www.nifc.gov/fireInfo/fireInfo\_stats\_totalFires.html"]~~2018-2023:~~ [HYPERLINK "https://www.nifc.gov/fire-information/statistics/wildfires"]

Note that the NIFC has removed the pre-1960 data from its current website. They claim it is because measurement methods changed after 1960. This explanation seems inadequate since agencies blend temperature and extreme weather data series in other contexts when measurement systems changed. ~~In this case if anything,~~ The measurement of wildfires has improved since the early 20<sup>th</sup> century, so any bias will be towards understating early wildfire counts. Nonetheless just focusing on the post-1985 interval the number of fires is not increasing. The area burned did increase but only until about 2007.

Forest fires have always been a part of nature, and they can certainly create conditions that are inhospitable in the short term for all life including humans. Science has confirmed the overall benefit and necessity of the occurrence of forest fires. While recent high-profile fires and seasons serve as a reminder of the potential destructive impact, the highest profile forest fire remains the 1910 Big Blowup fire which destroyed over three million acres including the elimination of entire towns like Taft, MT (Apple 2020). The 1910 fire reshaped the U.S. Forest Service (National Forest Foundation 2022) leading to a focus on fire suppression with a primary goal to defeat all forest fires (Forest History Society 2022). This led to the 10 am rule in 1935 that meant all fires spotted on any day had to be controlled by the following day at 10 am (National Forest Foundation 2022).

While defeating fire is certainly a noble goal, questions began to arise as to whether this behavior "followed the science" (US Forest Service 2022). Over time the U.S. Forest Service has begun to rethink its behavior, recognizing that new approaches such as prescribed burns, fuel elimination and controlled wildfires are more appropriate (Sommer 2016). Recent research is validating this approach and recognizing that more frequent smaller fires in forests likely result in the most healthy forests, water ecosystems and biodiversity (Stephens et al. 2021).

It is difficult to establish a natural baseline for wildfire activity because of active fire suppression activity since 1900. Paleoclimatic evidence indicates, however, that past wildfire activity was much higher than at present. Marlon et al. (2012) used sedimentary charcoal layers to reconstruct fire history of western US for the past 1400 years. They also fit a model to predict expected fire activity as a function of climatic conditions. The results are summarized in Figure 8.7.3.779.3 below (from Figure 2 in their paper).

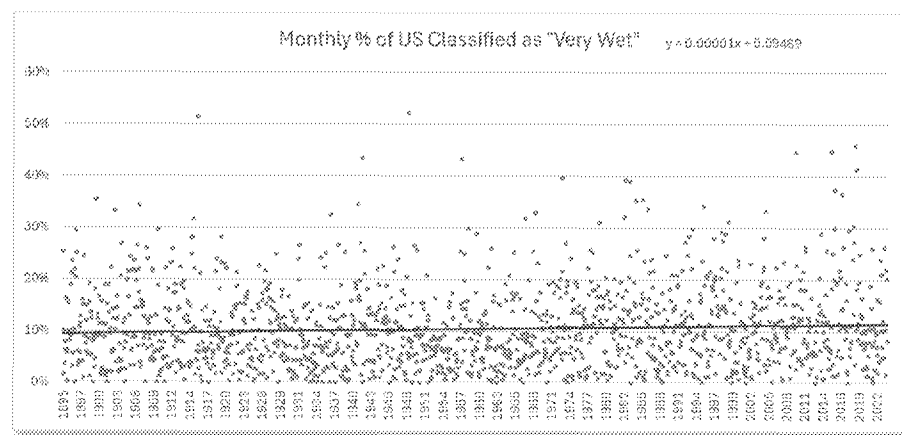


**Figure 8.23.37:** Fire frequency and fire deficit in the US. Source: Copied from Marlon et al. (2012)

In their figure the red line shows the smoothed charcoal record and the black dotted line shows the predicted charcoal record based on the statistical model. The gap at the end implies there has been a growing wildfire deficit over the 20<sup>th</sup> century. In other words, however much fire was observed in the 20<sup>th</sup> century it was less than what would have been observed in previous centuries based on the climatic conditions. Parks et al. (2025) likewise find that despite the recent increase in wildfire burn area in North America, a significant wildfire deficit remains relative to historical wildfire regimes there remains a significant wildfire deficit.

### 8.23.3 Precipitation

Figure 8.23.8 shows that US long-term data from NOAA shows an insignificantly increasing tendency toward extreme wetness (+0.0001% per year)



**Figure 8.23.8:** Long-term US wetness (%) Source: NOAA [HYPERLINK "<https://www.ncei.noaa.gov/access/monitoring/uspa/wet-dry/0>"]

Precipitation will be discussed further in the review of CONUS data below.

#### 8.23.4 Drought

As shown in Figure 8.3.9, US long term data (NOAA) shows an insignificantly declining tendency toward extreme dryness (-0.001% per year)

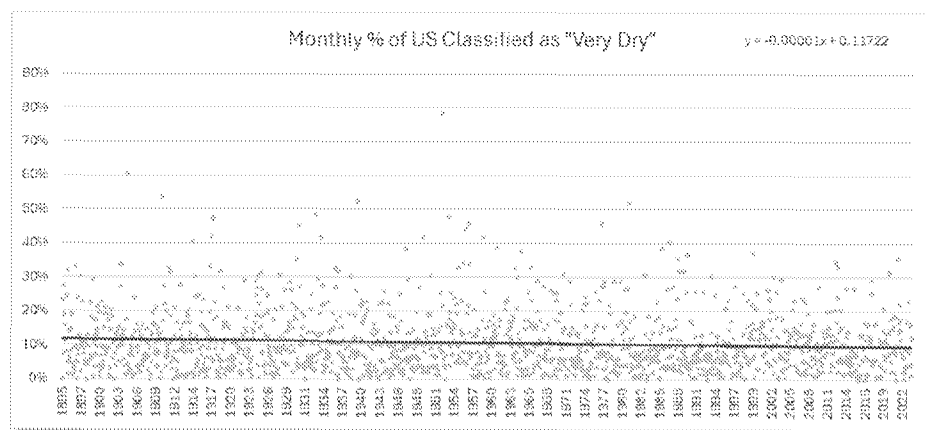


Figure 8.3.9: US dryness (%) 1895-2023. Source: NOAA [HYPERLINK <https://www.ncei.noaa.gov/access/monitoring/uspa/wet-dry/0/>]

Hogan et al. (2020) examines a 20-year high-resolution satellite-based drought measure and concludes that global drought has not intensified and is not connected to climate change. "It is possible to state firmly that global and main-grain countries' drought areas and intensity trends have not been following global climate warming since 1980's."

### 8.3.4 Analysis of Temperature and precipitation extremes in the Conterminous Contiguous US (CONUS) data on temperature and precipitation extremes

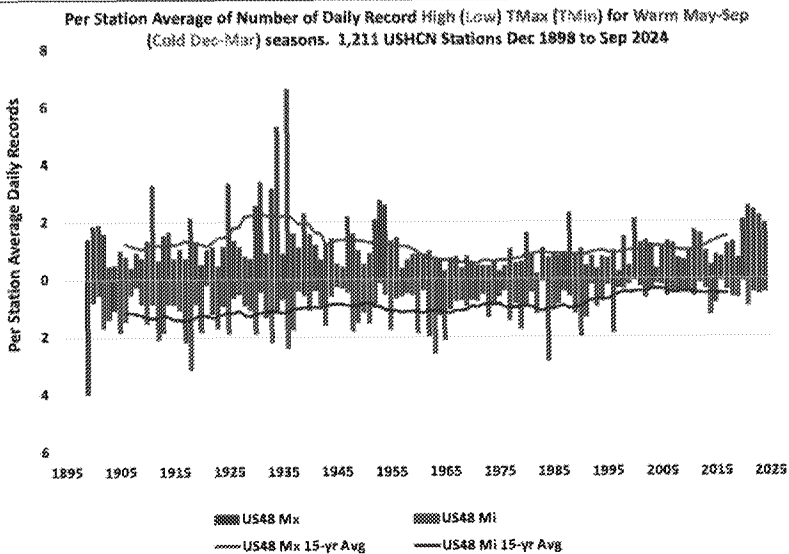
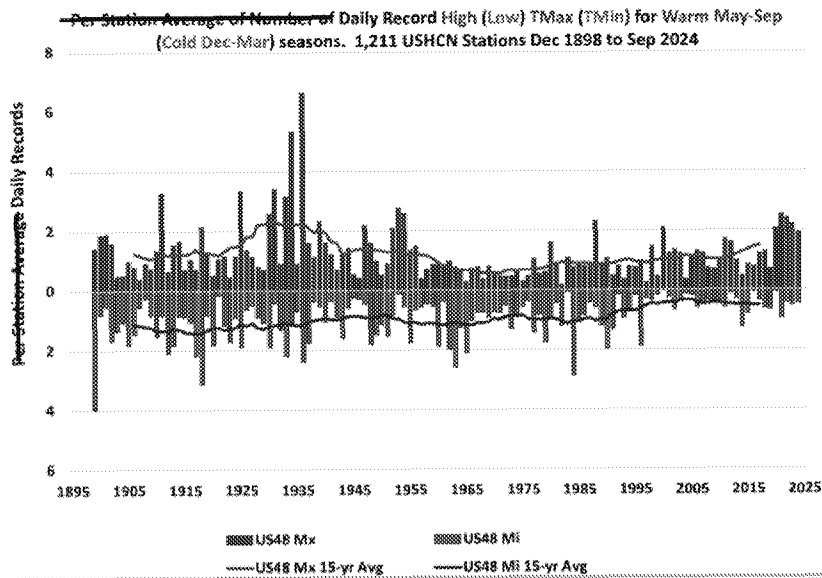
#### 8.34.1 CONUS daily temperatures are becoming less extreme

Daily maximum temperatures in the warm season (TMax, May-Sep) and daily minimum temperatures in the cold season (TMin, Dec-Mar) are available beginning in Dec-1898 (126 years). The dataset consists of 1,211 CONUS stations designated as United States Historical Climate Network or USHCN stations (Quinlan et al. 1987, Karl et al. 1990). These stations were selected by NOAA as having the fewest problematic issues with gaps, station moves and instrument changes. Where gaps still exist, nearby stations (bias-corrected) were merged so that the median volume of data available for a station is 98%. Although there are certainly errors certainly reside in the dataset, with over

**Commented [A14]:** Again, I think we need a map of where the stations are; something like this one:  
[HYPERLINK [https://www.researchgate.net/publication/258660497\\_Uncertainties\\_Trends\\_and\\_Hottest\\_and\\_Coldest\\_Years\\_of\\_US\\_Surface\\_Air\\_Temperature\\_since\\_1895\\_An\\_Update\\_Based\\_on\\_the\\_USHCN\\_V2\\_TOB\\_Data/figures?lo=1](https://www.researchgate.net/publication/258660497_Uncertainties_Trends_and_Hottest_and_Coldest_Years_of_US_Surface_Air_Temperature_since_1895_An_Update_Based_on_the_USHCN_V2_TOB_Data/figures?lo=1)] More importantly, it needs to show how you've cut them up into regions.

1,000 stations we can have relatively high confidence in any underlying signal we that might be discovered can be characterized by relatively high confidence.

We begin with the question of whether the occurrence of daily record high or low temperatures changed has changed since Dec 1898. Each warm season has 153 days (1 May to 30 Sep) and each cold season has 122 days (1 Dec to 31 Mar). For each station and day, we calculated the year in which the record highest (lowest) temperature occurred. With 126 years of observations, if there were no temperature trends over time, the expected number of records for TMax would be 1.21 ( $=153/126$ ) per station per year and for TMin 0.96 ( $=122/126$ ) per station per year. Figure 8.4.110 indicates the observed distribution in time of the occurrence of these extreme events.



**Figure 8.4.110** Number of daily record High (red) and Low (blue) for warm and cold seasons in the CONUS. The lines represent the 15-year running, centered average. Source: 1,211 USHCN stations supplemented as needed to achieve a minimum of 92% of observations in the 126-year period since Dec 1899.

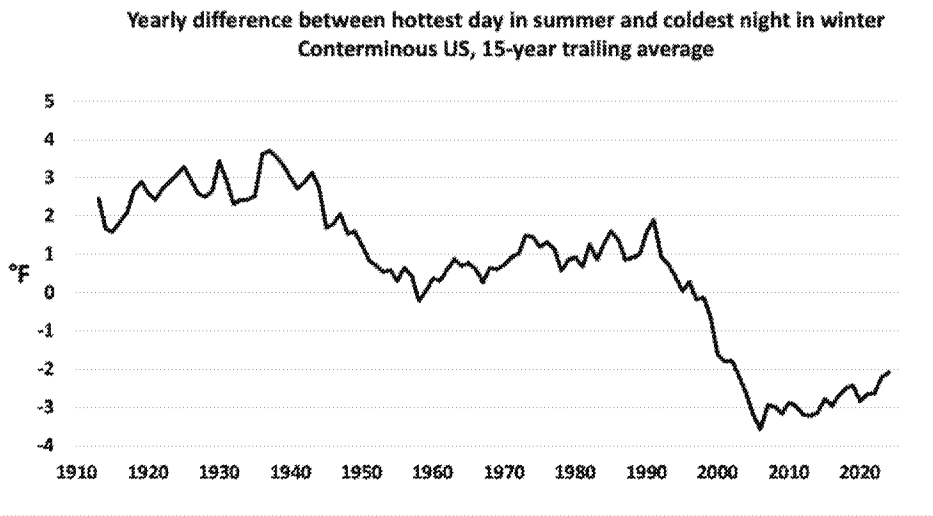


The results indicate a common feature in many metrics of warm-season extremes in the CONUS—the exceptional heat of the 1920s and especially the 1930s, peaking in 1936. On a per-station average, 60% of the TMax records and 59% of the TMin records occurred in the first half of the period (1899–1961).

On the cold-side, the Valentine's Day Arctic outbreak in Feb 1899 stands as the most extensive cold extreme experienced by the CONUS, with 1917–2<sup>nd</sup>. The frequency of cold records has declined, especially over the last quarter of the period in which only 13% of the extreme cold events were measured. In contrast, 25% of the extreme TMax records were achieved in the last quarter in accordance with statistical expectations. These general features have been noted in past assessments (IPCC AR5, IPCC AR6, NCA4, NCA5). Combining the two records the overall reduction in numbers of both cold and hot extremes over the past century indicates a climate less prone to extremes.

This pattern is also shown in Figure 8.4.211. For each station and for each year the hottest warm season and coldest cold-season temperatures were calculated and converted to anomalies relative to the station's long-term warm and cold season (respectively) averages. Then the differences between these were computed by station and geographically averaged over all stations, thus yielding an annual measure of the expected range of local extreme temperatures for each year. Figure 8.11 shows the 15-year trailing average of this measure which has clearly declined over the past century.

**Commented [A15]:** Does this include a correction for varying station density? If not, it should just read "averaged".



**Figure 8.4.211.** 15-year trailing average of the difference each year of each station's hottest warm-season TMax and coldest cold-season TMin relative to the long-term average.

The average difference for each station between the hottest summer TMax and coldest winter TMin has declined about 5°F in the past 126 years. The decline is due mostly to warming winter TMin, but

a decline in the magnitude of summer TMax is also a factor. The rise in TMin has been strongly related to the growing presence of manufactured surfaces around the weather stations over the last 100+ years (Spencer et al. 2025).

Summarizing Figures 8.10.4.1 and 8.4.2.11, while temperature extremes are regularly experienced in the US and attract a great deal of media attention, long term records show the US climate has become less extreme over time (milder) when measured in terms of the range between warm season maxima and cold season minima.

#### **8.34.2 Exceedances of a heat threshold**

Under the heading of "The Risk of Temperature Extremes is Changing", the most recent US National Climate Assessment report (NCA5) notes the increase in a threshold metric of number of days at or above 95°F, stating,

*"The western US has been particularly affected by extreme heat since the 1980s ..., experiencing a larger increase in days over 95°F, as would be expected given the greater warming in that region relative to the eastern US. Several major heatwaves have affected the US since 2018, including a record shattering event in the Pacific Northwest in 2021."*

Are the occurrences of 95°F days changing? In a climate as varied as that of CONUS, threshold statistics can be misleading. A region with many stations which ~~that~~ have near 95°F TMax average temperatures in the summer might see large swings in the metric when only small changes in average temperature occur. Elsewhere with stations that either rarely or virtually always achieve 95°F TMax temperatures, a small change will not impact the results much at all. In the past 126 years, the average CONUS station experienced 129 days exceeding 95°F per 6-yr period, but the regional values range from 278 in the Southern Plains to 9 in the Northeast. Thus, one needs to view such threshold analyses with caution.

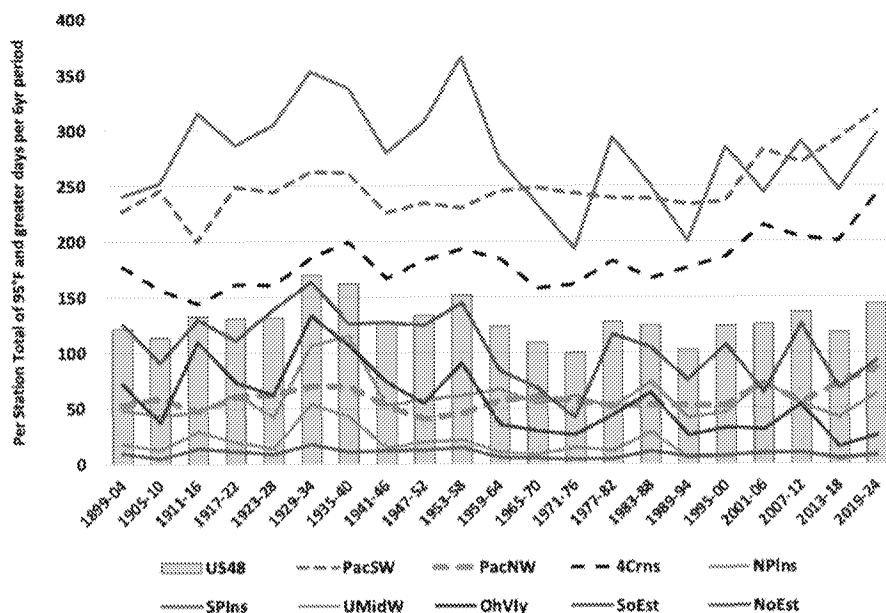


Figure 8.124.3. Total number of days  $\geq 95^{\circ}\text{F}$  in 6-yr periods, US 48 (bars) and regions (lines).

In Fig. 8.12 4.3 we see that only three of the nine regions, all in the West, have experienced upward trends in the number of  $95^{\circ}\text{F}$  or hotter days (dashed lines). The CONUS as a whole has not and the other six regions have experienced declines.

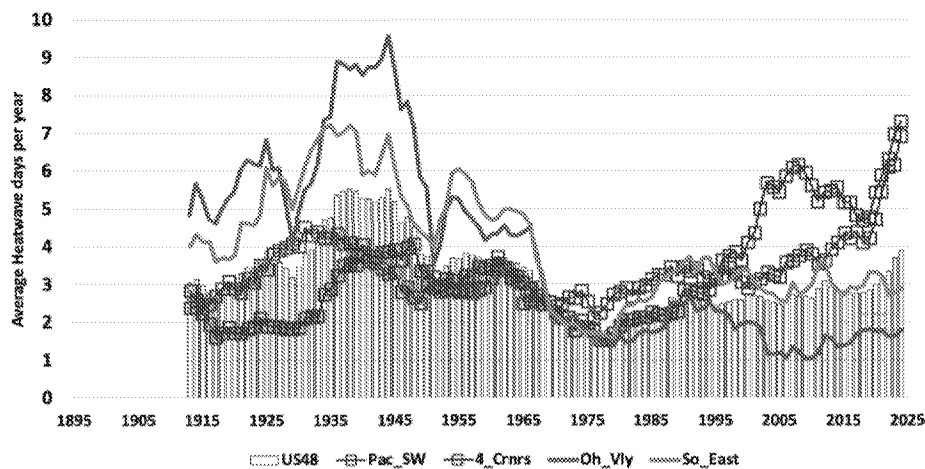
The Pacific NW heatwave of 2021 is referenced as supportive information for of the NCA5 claim, an event we examined more closely in Section 6.4. The evidence indicates it was a “black swan” event, i.e., a single, unprecedented event in the existing record, not part of a suggesting it is not indicative of a pattern of increasing extreme heat. For example, the 5-day average tropospheric grid-point temperature anomaly over the Pacific NW during that event was  $+10.8^{\circ}\text{C}$ , the most extreme NH grid point summer anomaly in the 46 years from over 4 million grids. In contrast, the global anomaly during that time was virtually zero ( $+0.03^{\circ}\text{C}$ , Mass et al. 2024).

The heading “The Risk of Temperature Extremes is Changing” suggests positive trends are now being observed in threshold temperatures on a widespread basis, but that is not evidenced in the combined CONUS results of the figures above.

### 8.34.3 Heatwaves

Heatwaves (consecutive days that exceed an extreme threshold) have a greater societal impact than Of more impact than a single daily record. We measure is the phenomena of heatwaves, or consecutive days which exceed an extreme threshold. For this study, the metric will be the number of “Heatwave Days” here defined as the sum count of all days in May-Sep each year which that exceed

the 90<sup>th</sup> percentile and that occur lie within consecutive periods a run of at least six consecutive days in length. This is equivalent to the method used in NCA5 except that the reference period here is the entire record 1899-2024 while NCA5 limited truncated the reference period to 1961-1990, a cool episode time. By selecting 1961-1990, the that truncation occurrence of boosts positive results (days exceeding the 90<sup>th</sup> percentile) will be enhanced in periods warmer than the reference base period, especially if starting in 1960 and moving to the present (see *Urban Influences* below).



**Figure 8.13 4.4** 15-year trailing average of number of heatwave days per year per station in the CONUS (bars) and four regions: Pac\_SW (purple squares, CA, NV), 4\_Crnrs (red squares, AZ, NM, UT, CO), Oh\_Vly (blue, MO, IL, KY, TN, IN, OH, WV) and So\_East (green, MS, AL, GA, FL, SC, NC, VA).

Figure 8.13 4.4 indicates again the excessive heat of the first half of the 20<sup>th</sup> century, primarily in the eastern two-thirds of the nation, as seen in the regional values for the Ohio Valley and the Southeast as examples. The West has seen a recent increase of heatwave days and the two regions with the highest number are shown, the Pacific Southwest and the Four Corners (NCA5). This indicates that the background warm season circulation favored heatwaves in the eastern portions of the country in the first half of the 20<sup>th</sup> century, but in the 21<sup>st</sup> century the patterns have favored heatwaves in the West. For CONUS as a whole, heatwaves are no more common today than they were a century ago.

Of interest here is the regional variation of this metric. The four northern regions (Pacific NW, Northern Plains, Upper Midwest, and Northeast) on average experience 15 to 27 heatwave days per 15-year period. In contrast, the five southern regions (Pacific Southwest, 4-Corners, Southern Plains, Ohio Valley and Southeast) see 37 to 54 such days, essentially twice as many. This suggests the summer circulation pattern is more prone to stationary events in the southern regions while transient systems in the northern regions are more common and thus cut short these potentially longer events.

#### *Urban influences*

The NCA5 directs readers to the website [HYPERLINK "https://www.globalchange.gov/indicators/heat-waves"] (USGCRP 2023) to view the number of urban heatwaves by decade from the 1960s. The figure reveals ~~shows~~ a monotonic increase in each decade from 2 occurrences per year in the 1960s to 6 in the 2020s. The definition of a heatwave is ~~an unusual but practical measure from a of human discomfort perspective~~ a period of at least 2 consecutive days when the ~~minimum~~ apparent minimum temperature (combination of temperature and humidity) exceeds the 85<sup>th</sup> percentile. Note too, the dataset is limited to the 50 largest U.S. cities in the US.

These increasing values since 1960 presented in USGCRP (2023) are entirely reasonable, but are ~~unrelated to GHG emissions for at least two reasons unrelated to GHG emissions~~. Urbanization in these cities is a major factor in the rise of TMin relative to co-located TMax and relative to TMin at rural stations. Also, the 1960s was the coldest decade and 1970s the second coldest decade since the 1910's, so this starting date preconditions the time series to show increases. This does not dismiss the real rise in nighttime temperatures in major U.S. cities and the societal impacts associated with these changes. However, we note for a variety of reasons, that summer TMax (especially in rural areas) serves as better response variable for detecting potential changes in heatwaves influenced by changes in the background climate due, for example, to increasing GHGs (Christy et al. 2009). For the CONUS as a whole, the evidence in this section suggests GHG emissions have had little to no effect on heatwaves in the CONUS.

#### 8.34.4 Extremes in daily precipitation.

~~Because precipitation involves a discrete phase change (water vapor to liquid), it is~~ Due to its stochastic and episodic in character and therefore, precipitation requires careful statistical treatment to understand variability over long time periods (see 8.1 Introduction). The US National Climate Assessments (NCA4, NCA5) have highlighted an increase in the occurrence of the heaviest precipitation events (defined in different ways) primarily in the eastern half of the CONUS, especially the Northeast, when starting in either 1901 or 1958. Interestingly, the regional variations indicate that the largest increases in extreme events are in the Northeast and least the smallest in the West, which is a trend counter to the changes in temperature extremes shown above.

Commented [A16]: Stochasticity and LTP are really different things, but we somehow conflate them in this sentence. Or am I missing something?

Commented [A17R16]: By removing the 'therefore' I think we are now not conflating them.

McKittrick and Christy (2019) examined long-term and consistent station observations of daily precipitation to test some of these NCA claims for the Southeast and West Coast. In neither case ~~When the time series were extended back in time (as far as 1872 in some cases) or when starting later (1978), there were no~~ were the trends significant trends for either region. For this report we updated these findings with similarly constructed observations from 29 stations on the Pacific Coast (1893ff from San Diego CA to Blaine WA, see Figure 8.14), 24 stations in the humid Southeast (1872ff from Austin TX to Washington DC, see Figure 8.15), and 21 stations in the Northeast (1888ff from Buffalo NY to Gardiner ME, see Figure 8.16). The results were as follows:

##### Pacific region:

- ~~Average precipitation trend is significant (downwards) in Astoria, insignificant elsewhere.~~
- ~~The trend in rainfall variance is positive and significant in Big Sur, insignificant elsewhere.~~
- ~~The trend in daily maximum precipitation is positive and significant in Aberdeen and Big Sur and negative and significant in Newport (insignificant elsewhere).~~
- ~~Averaged over all stations in the region none of these three trend parameters is statistically significant.~~

##### Southeast region:

- ~~— The trend in average precipitation is positive and significant in Mobile and Quitman, insignificant elsewhere.~~
- ~~— The trend in rainfall variance is positive and significant in Mobile, insignificant elsewhere.~~
- ~~— The trend in daily maximum precipitation is positive and significant in Vicksburg and Norfolk, insignificant elsewhere.~~
- ~~— Averaged over all stations in the region none of these three trend parameters is statistically significant~~

#### Northeast region:

- ~~— The trend in average precipitation is positive and significant in 9 of 21 locations and in the region averaged overall.~~
- ~~— The trend in rainfall variance is positive and significant in Portland, Albany and Buffalo, insignificant elsewhere.~~
- ~~— The trend in daily maximum precipitation is positive and significant in Portland and Gardiner, insignificant elsewhere.~~
- ~~— Averaged over all stations in the region the trend parameters for variance and maximum precipitation are not statistically significant.~~

~~In the Pacific region, over the whole sample, the trend in average precipitation trends downward, being significant only is negative and significant in Astoria, and insignificant elsewhere. The trend in rainfall variance increases, is positive and significant only in Big Sur, and insignificant elsewhere. The trend in daily maximum precipitation is positive and significant in Aberdeen and Big Sur and negative and significant in Newport and insignificant elsewhere. Averaged over all stations in the region none of these three trend parameters is statistically significant.~~

~~In the Southeast region over the whole sample the trend in average precipitation is positive and significant only in Mobile and Quitman, the trend in rainfall variance is positive and significant only in Mobile and the trend in daily maximum precipitation is positive and significant only in Vicksburg and Norfolk. Averaged over all stations in the region none of these three trend parameters is statistically significant.~~

~~The Northeast region exhibits a pattern of increasing average rainfall. The trend in average precipitation is positive and significant in 9 of 21 locations and in the region averaged overall. The trend in rainfall variance is positive and significant only in Portland, Albany and Buffalo and insignificant elsewhere and not in the regional average. The trend in daily maximum precipitation is positive and significant only in Portland ME and Gardiner ME and insignificant elsewhere and not in the regional average. ]~~

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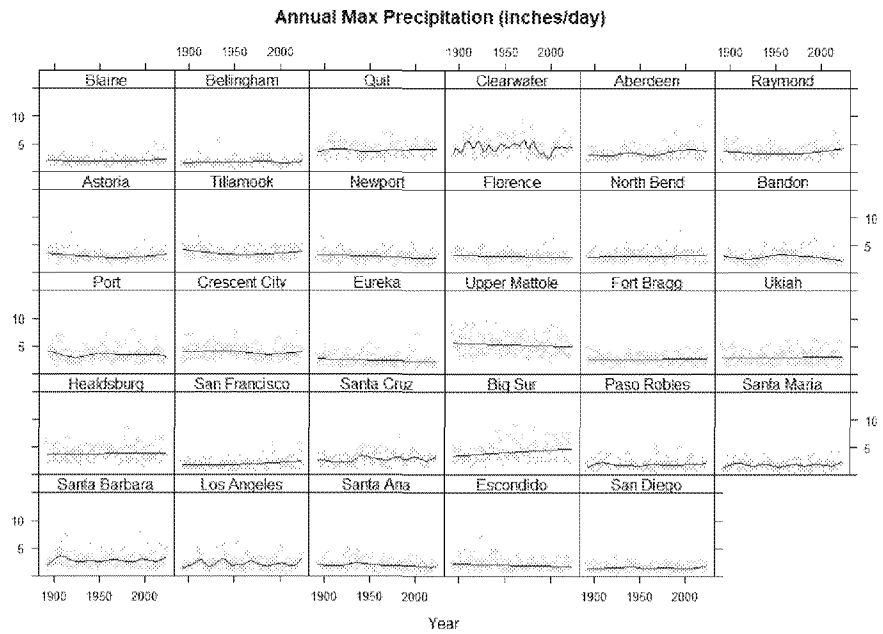
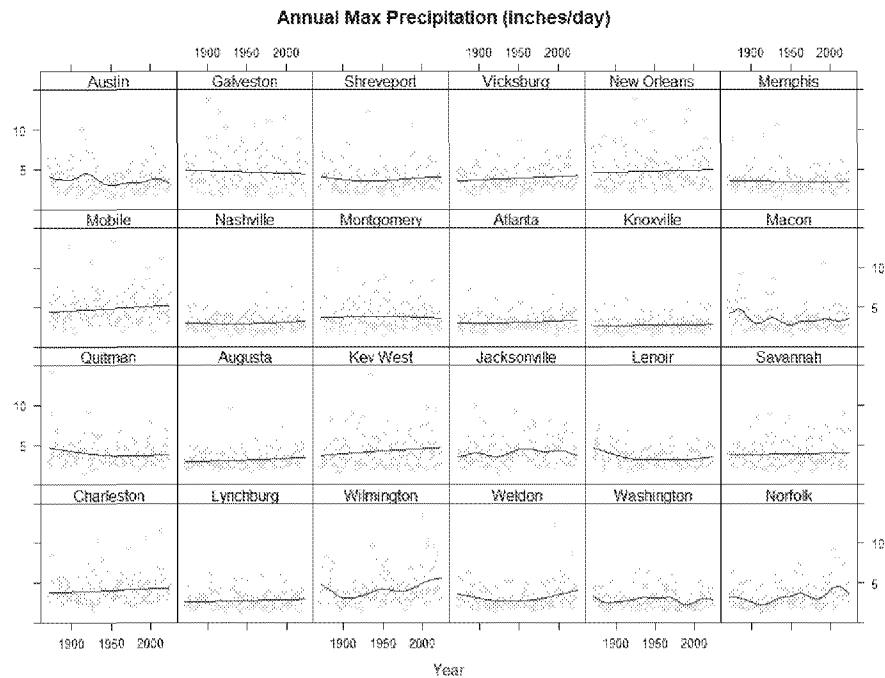
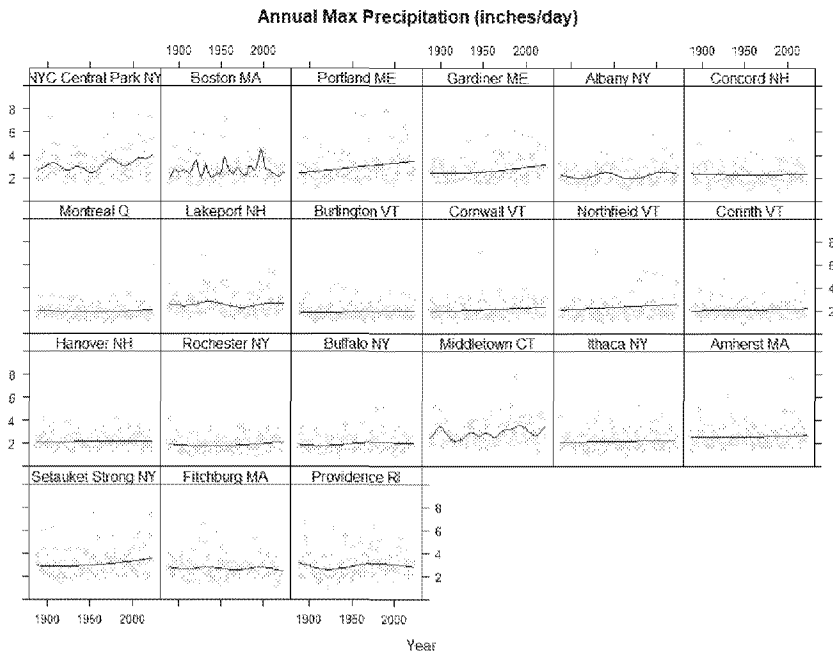


Figure 8.11 Annual maximum precipitation for 29 Pacific stations 1893 to present



**Figure 8.12** Annual maximum precipitation for 24 Southeast stations 1872 to present





**Figure 8.13** Annual maximum precipitation for 21 Northeast stations 1888 to present

#### *Pacific Coast heavy rainfall events*

The Pacific Coast receives considerable amounts of precipitation from Atmospheric River (AR) events which often last more than a day or two (e.g., Gershunov et al. 2017, Pan et al. 2024). The worst known such event in recent history was the ArkStorm that occurred between December 1861 and January 1862, which dumped nearly 10 feet of rain in parts of California and submerged the entire Central Valley for weeks under as much as 15 feet of water (Brewer 1930, Null and Hulbert 2007). Paleoclimate research has found six megastorms more severe than 1861–1862 in California during the last 1800 years, occurring at intervals of 300 years or so (Porter et al. 2011).

#### **SIDEBAR: Perils of short data records**

San Francisco provides a good case study of the limitation of using short historical samples to characterize natural variability of extreme events. Suppose we use a 130-year sample of daily San Francisco precipitation from 1895 to 2024 and we look for 3-day, 5-day, 14-day and 30-day rainfall records. The results are as shown in Table 8.12.

| Event  | Record (inches) | Year |
|--------|-----------------|------|
| 3-day  | 6.94            | 2023 |
| 5-day  | 8.55            | 2023 |
| 14-day | 12.62           | 2023 |

30-day 18.93 1998  
Table 8.12: Extreme rainfall records, San Francisco, 1895-2024.

The records all cluster in the more recent data. 2023 appears to be an exceptional year and since it is near the end of the sample it would ~~might~~ point to the possibility ~~suggest~~ that the climate has shifted into a potentially more hazardous state, ~~perhaps as a result of human influences.~~

But the picture is very different if we use a sample that begins ~~45~~ years earlier, in 1850. If we extend the record back to 1850 the picture changes. Table 8.23 shows that the record-setting events ~~then~~ all happened in the 1860s. Furthermore 2023 is now not even in 2<sup>nd</sup> place but falls to 3<sup>rd</sup> or 4<sup>th</sup>. Also, comparing the records of the two charts the extreme precipitation events in 1862 and 1867 involved considerably more rainfall than the 1998 and 2023 events, with 14- and 30-day totals about 50 percent higher.

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| Event  | Record (inches) | Year | Rank of 130-yr extreme |
|--------|-----------------|------|------------------------|
| 3-day  | 8.85            | 1867 | 3                      |
| 5-day  | 9.80            | 1867 | 3                      |
| 14-day | 19.05           | 1862 | 4                      |
| 30-day | 28.25           | 1862 | 2                      |

Table 8.23: Extreme rainfall records, San Francisco, 1850-2024.

~~The~~ The characterization of the range of natural variability is made even more remarkable when paleoclimate evidence is examined. Porter et al. (2011) discovered that in the past 1,800 years at least six megastorms were more intense than the devastating 1861-62 ArkStorm ~~that~~ struck the region. Thus, ~~Evidently~~ such extreme events have impacted the region about every 300 years, though not since 1895.

This example illustrates the limitations of using relatively short climate periods (~130 years) to assess the character and range of natural variability in general and of extreme events in particular. Accurate representation of the full range of natural variability is necessary for any attribution analyses (see 6.4). Infrastructure planners, emergency management institutions and attribution scientists would understand the significant mischaracterization of the magnitude of a future extreme if based only on the last 130 years. In this case, a single time-sample of 130 years provides an underestimation of the extreme value by up to 50% determined when adding only 45 more years of observations. Compared to millennial-scale paleoclimate evidence, an even greater underestimation would occur. ~~An important lesson is that the climate can deliver great surprises on its own, even without human influences.~~

We examine occurrences of 5-day deluges as follows. In a 130-year span there are 26 5-year intervals. At each location we computed the 5-day precipitation totals throughout the year and selected the 26 highest values. A single year may have more than one of the 26 heaviest. Each of those can be thought of as 1-in-5yr events. If there are no trends in precipitation then the total number of these events across all stations should be evenly spread out on an annual basis ~~over the years~~. In Fig. 8.14.4.5 we show the distribution in time of these events. The deluges associated with the massive 1997-98 El Niño event are readily apparent. While erratic, as is typical of these types of precipitation metrics, there is no indication of a tendency to become more frequent over time.

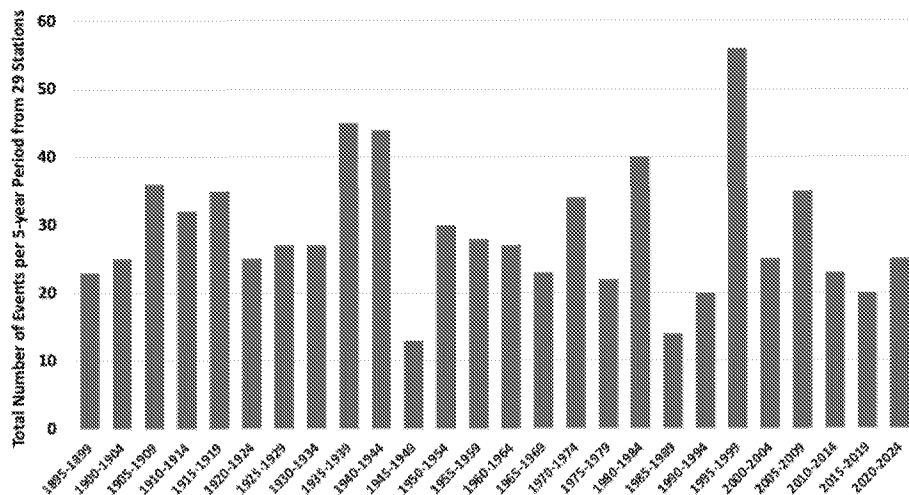
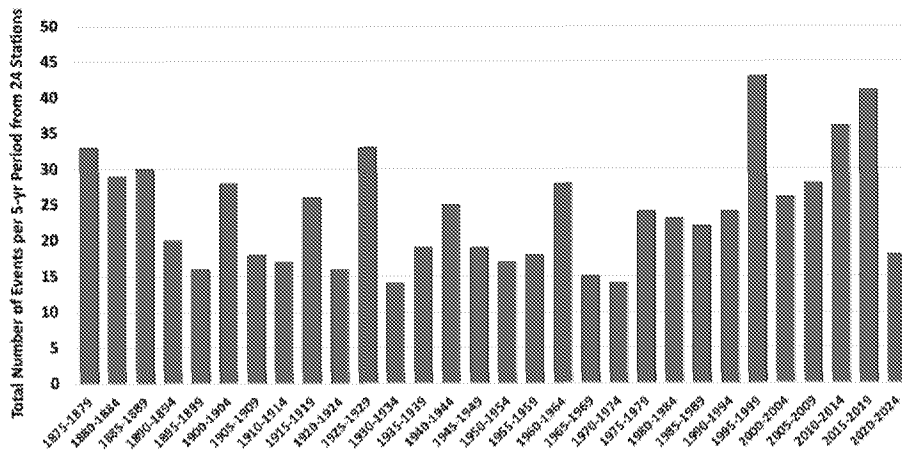


Figure 8.144.5 The time distribution by 5-year periods of the 26-heaviest occurrences for each station (i.e., nominal 1-in-5 year event).

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#### *Southeast heavy rainfall events*

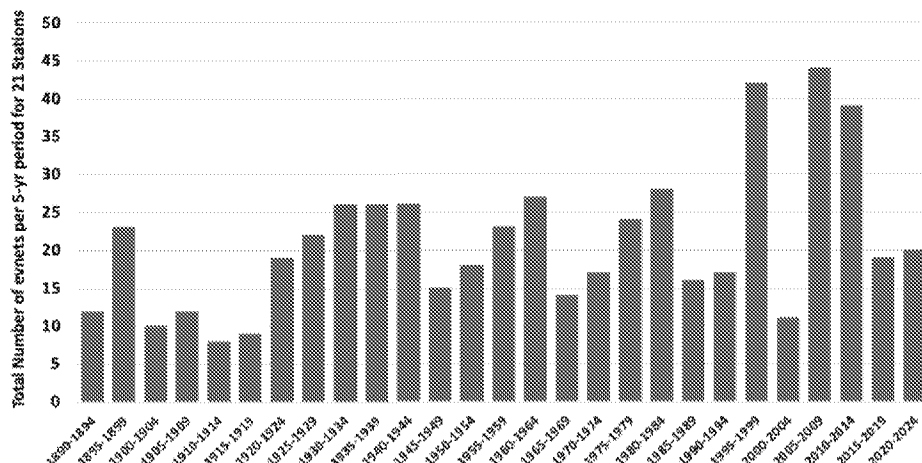
The temporal pattern of 5-day totals of the 1-in-5yr heavy events in the humid Southeast (Figure 8.154.6) is generally unremarkable, though a cluster of higher values appears in 1995 to 2019. The increase in those years is due largely to the 4 northeastern-most stations of Wilmington NC, Weldon NC, Washington DC, and Norfolk VA. This confirms the pattern indicated in NCA4 and NCA5 of a tendency for an increasing frequency of heavy events, due to a temporal clustering of tropical storms from eastern NC to Maine discussed below. Otherwise, the remaining 20 stations show an unremarkable temporal distribution of heavy events.



**Figure 8.154.6.** As above but for the 30 heaviest 1-in-5yr events for 24 stations in the humid Southeast from Austin TX to Washington DC in 5-year bins for 1875-2024.

#### Northwest heavy rainfall events

Fig. 8.16.4.7 shows the 27 (1-in-5yr) heaviest 3-day events for the last 135 years in 21 stations in the Northeast (including Montreal Canada). We use 3-day totals here as this produced the largest variations in time. In this region, 72% of the events occur during June to October and are dominated by tropical incursions of hurricanes, tropical storms or tropical storms that transition to extratropical systems. According to NCA4 and NCA5 this region experienced the largest increases in extreme events, so it shall be examined more closely.



**Figure 8.164.7.** Time distribution of the heaviest 27 (1-in-5yr) heaviest 3-day precipitation events for 21 stations from NY to ME, including Montreal.

Howarth et al. (2019) report differences in the Northeast between two 18-year periods: 1979-96 and 1997-2014 (a similar region as in Fig. 8.16 that includes PA and NJ) of various precipitation extremes. One metric which indicated a dramatic increase (317%) was found for 24-hr events > 6 inches. This high increase is due to the very small numbers of such events of which there were only 6 in the first period and 25 in the second as reported for 58 stations. This high percentage increase is due to the very small numbers of the events; only 6 in the first period and 25 in the second. Most of the stations did not record such an event suggesting these erratic, episodic events over brief, 18-yr periods, need scrutiny by additional statistical methods.

Using the information in Fig. 8.16 4.7, over the same years as Howarth et al. we find a 51% increase in the frequency of heavy events between the two periods. One can see in Fig. 8.16 that it was unfortunate that Howarth et al. ended in 2014 prior to a return to the long-term average of such events.

A feature of Howarth et al. is the use of single day totals which is questionable because extreme events are often spread across the time of observation boundary. Thus stations measuring at 0700 LT versus those at Midnight will have differing results for a particular event which would then have major impacts on counting these events. We use the 3-day totals in Fig. 8.16 4.7 to be sure to capture the extent of these extreme downpours. In any case, we can confirm that the period 1997 to 2014 experienced a cluster of heavier events as Howarth et al. have documented.

Howarth's most remarkable claim (317% increase in 6" days) is potentially misleading because it is a threshold statistic (see Section 8.34.2 above) and a ratio of small numbers over a short period. The result is not representative of *relative* extreme events for the whole region since the majority of stations never experienced a 6" total. Fig. 8.16 above determines the same number of events for each station (27 heaviest events) whose heaviest values ranged from 4.4" to 12.5" and their 27<sup>th</sup> heaviest values ranged from 3.3" to 5.0". This analysis thus allows each station to be equally represented. In

other words, if there is a region-wide increase in heavy events, it should be seen in the sum of all stations. Note too that the period of record here is 135 years vs. 36 years of Howarth et al. Except for three 5-year periods between 1995 and 2014 there is nothing statistically remarkable about the results in Fig. 8.164.7.

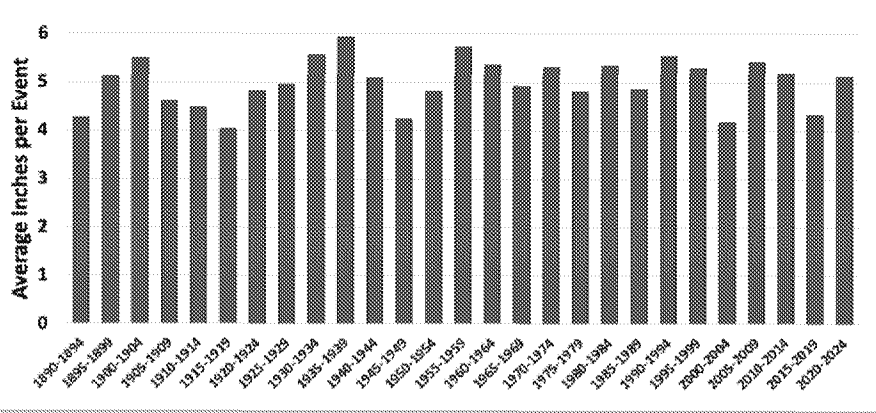


Figure 8.174.8. Average amount of precipitation falling in the 1-in-5yr events for the NE stations.

An interesting aspect of Northeast precipitation is that there has been no change in the amount of precipitation per heaviest event, as shown in Fig. 8.174.8. The trend is only +0.02"/decade. The highest amount, 1935-39, includes the Great New England Hurricane of 1938, one of the rare major (Category 3 or higher) hurricanes to strike the region. The results in Figs. 8.4.615 and 8.16.4.7 suggest that though there was an uptick in the number of events during the period 1995 to 2014, the events, individually, are not becoming more intense.

Jong et al. (2024) document the increase of tropical influences on precipitation events in the Northeast since 1959 and concluded, "The autumn extreme precipitation trend over the Northeast US is primarily attributed to tropical cyclone-related events since the 1990s." The question then becomes, was the temporal clustering of tropical systems in 1997-2014 which affected the Northeast a response to increasing GHGs? Jong et al. examined CMIP-6 model output which suggests that there will be fewer such systems in the 21<sup>st</sup> century but that the intensity of the rainfall events might increase. This conjecture is not seen in Fig. 8.17 where the amount per event has remained steady over the 135-year period.

For substantial urban areas there is some evidence to indicate the heaviest rainfall events may be redistributed due to the impact urban infrastructure has on the local weather (e.g., Pielke Sr. et al. 2011, Zhang et al. 2018, Yang et al. 2024). Yang et al. state, "Cities that experience compact development tend to witness larger increases in extreme rainfall frequency over downtown than their rural surroundings, while the anomalies in extreme rainfall frequency diminish for cities with

dispersed development." While this is an important insight to consider, the effect on the specific stations used in this analysis is unknown, or at least not detectable in Fig. 8.17.

In summary, the evidence from the historical record of extreme precipitation events in the CONUS is generally not consistent from region to region so that inferences regarding trends and their projections are wrought with significant uncertainty. In most regions and perhaps all, it is our opinion that the very nature of the erratic and episodic character of extreme precipitation events renders the discovery of statistically significant changes, including a relationship to CO<sub>2</sub> concentrations, a result yet to be achieved (McKittrick and Christy 2019).

#### 8.7.4510 Summary

Contrary to popular belief and frequent claims by the media and many political leaders, most types of extreme weather exhibit no statistically significant trends, nor do assessment reports of the IPCC or the NCA claim to have detected any. There has been an increase in hot days in the US since the 1950s, a point emphasized by the IPCC AR6, but a decrease relative to the 1920s and 1930s. Extreme convective storms, hurricanes, tornadoes, floods and droughts exhibit considerable natural variability but long-term trends are not detectable. Some increases in extreme precipitation events can be detected in some regions over short intervals but over long periods and at the regional scale the trends do not persist. Wildfire activity has increased in the US in recent decades but has declined globally and in the US is down significantly compared relative to the early 20<sup>th</sup> century and to the estimated natural baseline level. Changes in US wildfire activity are strongly affected by changing forest fire management practices.

To be inserted

Based on the content provided in the document, here are the five most important takeaways:

- Limited Detection of Anthropogenic Signals: The IPCC has asserted high confidence in detecting an anthropogenic signal in only 4 out of 34 weather impact categories, and medium confidence in 4 more. For the remaining 26 categories, no anthropogenic signal is claimed to be detected.
- Slow Emergence of Trends: Even under the most extreme forcing scenario (RCP8.5), the IPCC expects very few anthropogenic trends to emerge within this century for most weather impacts.
- Natural Variability Dominance: Natural variability continues to dominate patterns of extreme weather systems. Simple assertions of trend detection are often complicated by regional heterogeneity and trend reversals over time.
- RCP8.5 Scenario Implausibility: The document notes that the RCP8.5 scenario is described as an implausible high-end storyline, not a "base case" or "business-as-usual" projection.
- Conflicting Messages on Attribution: The document mentions that AR6 (IPCC Sixth Assessment Report) offers conflicting messages about the attribution of extreme weather to anthropogenic causes, highlighting the complexity and uncertainty in this area of climate science.

These takeaways emphasize the nuanced and complex nature of attributing extreme weather events to climate change, and the importance of considering natural variability and uncertainty in climate projections.

Commented [A21]: Out of curiosity (and perhaps utility), I fed the entire document (absent this section) into Anthropic's Claude-3.5-sonnet LLM and asked it what are the five most important takeaways. This is what it produced. I'd judge it not a bad start that will need some human improvement, which I'll undertake on the next iteration.

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## Appendix: Review of IPCC and NCA Findings on Extreme Weather

The sources we review will be denoted as follows:

**SREX:** The IPCC *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (2012)

**AR5:** The IPCC *Fifth Assessment Report Working Group 1* (2013).

**AR6:** The IPCC *Sixth Assessment Report Working Group 1* (2021).

**NCA17:** The *US Climate Science Special Report of the Fourth National Climate Assessment* (2017) Volume I Chapter 6.

### 8A.1 Overview: IPCC Assessment of signal emergence in extreme weather types (AR6 WG1 Table 12.12)

Table 8A.1 reproduces the findings of AR6 Table 12.12 which indicates, for 34 major weather event and impact types, whether a signal of anthropogenic forcing has been detected in the historical record (column 1), whether such a signal is likely to emerge by 2050 under the extreme RCP8.5 scenario (column 2) and whether it is likely to emerge by 2100 under RCP8.5 forcing (column 3). It should be borne in mind that the latter two columns suffer from the deficiencies of GCMs discussed in Chapter XX. And as we discussed in Ch X on attribution, AR6 offers three conflicting messages within the AR6 regarding about attribution of extreme weather. Nevertheless, we provide This Table is provided here for reference.

Several patterns stand out. First, detection of an anthropogenic signal is asserted with *high confidence* in only four out of the 34 weather impact categories an anthropogenic signal is asserted with *high confidence* in only four, and with *medium confidence* in a further four. For the rest The IPCC does not *NOT* claim to have detected an anthropogenic signal in the remaining 26 categories. drivers. Of the four *high confidence* assertions, two are for changes in average temperatures (air and ocean), which hence are not measures of extreme weather. Also two Further, two of the four *medium confidence* assertions are related to ocean chemistry and thus are likewise also not related to extreme weather. The IPCC does not *NOT* assert a detectable human influence on many non-temperature weather features such as wind, precipitation, flooding, and drought, etc.

Second, as shown in, columns 2 and 3 show that the IPCC expects very few such anthropogenic trends signals to emerge within this century, even under the most extreme forcing scenario. As we discuss in Section 4.2 the RCP8.5 scenario is an implausible high-end storyline, it is not a “base case” or “business-as-usual” projection. Yet even still Even so, most weather impacts are not expected to exhibit show an anthropogenic signal this century. As will be clear from the underlying report text, nNatural variability dominates patterns of extreme weather systems and simplistic assertions of trend detection are frequently undermined by regional heterogeneity and trends reversals over time.

| Climate Impact Driver Type | Climate Impact Driver Category | Already Emerged in the Historical Record? | Emerging by 2050 in Most Extreme CO <sub>2</sub> Emissions Scenario? | Emerging by 2100 in Most Extreme CO <sub>2</sub> Emissions Scenario? |
|----------------------------|--------------------------------|-------------------------------------------|----------------------------------------------------------------------|----------------------------------------------------------------------|
| Heat & Cold                | Average air temperature        | YES in most regions                       | YES                                                                  | YES                                                                  |
|                            | More heat extremes             | YES in most regions                       | YES in land regions                                                  | YES                                                                  |
|                            | Fewer cold extremes            | YES in a few regions                      | YES in many regions                                                  | YES                                                                  |
|                            | Less frost                     | NO                                        | NO                                                                   | NO                                                                   |

|              |                                        |                          |                       |                       |
|--------------|----------------------------------------|--------------------------|-----------------------|-----------------------|
| Wet & Dry    | Average precip. (increase or decrease) | NO                       | YES (incr) YES (decr) | YES (incr) YES (decr) |
|              | River flooding                         | NO                       | NO                    | NO                    |
|              | Heavy precip. & pluvial flood          | NO                       | NO                    | YES in a few regions  |
|              | Landslide                              | NO                       | NO                    | NO                    |
|              | Aridity                                | NO                       | NO                    | NO                    |
|              | Hydrologic drought                     | NO                       | NO                    | NO                    |
|              | Agricultural & ecological drought      | NO                       | NO                    | NO                    |
| Wind         | Fire weather                           | NO                       | NO                    | NO                    |
|              | Average wind speed                     | NO                       | NO                    | NO                    |
|              | Severe wind storm                      | NO                       | NO                    | NO                    |
|              | Tropical cyclone                       | NO                       | NO                    | NO                    |
| Snow and Ice | Sand and dust storm                    | NO                       | NO                    | NO                    |
|              | Snow, glacier & ice sheet              | NO                       | YES in a few regions  | YES Arctic snow       |
|              | Permafrost                             | YES                      | YES                   | YES                   |
|              | Lake & river ice                       | NO                       | YES                   | YES                   |
|              | Arctic sea ice                         | YES                      | YES                   | YES                   |
|              | Antarctic sea ice                      | NO                       | YES                   | YES                   |
|              | Heavy snowfall and ice storm           | NO                       | NO                    | NO                    |
|              | Hail                                   | NO                       | NO                    | NO                    |
|              | Snow avalanche                         | NO                       | NO                    | NO                    |
|              | Relative sea level                     | NO                       | YES                   | YES                   |
| Coastal      | Coastal flood                          | NO                       | NO                    | NO                    |
|              | Coastal erosion                        | NO                       | NO                    | NO                    |
|              | Coastal upwell                         | NO                       | NO                    | NO                    |
| Open Ocean   | Average ocean temperature              | YES                      | YES                   | YES                   |
|              | Marine heat wave                       | NO                       | NO                    | NO                    |
|              | Ocean acidity                          | NO                       | YES                   | YES                   |
|              | Ocean salinity                         | YES                      | YES                   | YES                   |
| Other        | Dissolved oxygen                       | YES (Pacific & S. Ocean) | YES                   | YES                   |
|              | Air pollution weather                  | NO                       | NO                    | NO                    |

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## 89 Uncertainties in Climate Change Attribution

### Chapter summary

*"Attribution" refers to determining cause regarding some aspect of climate change, specifically with reference to anthropogenic activity. There is an ongoing scientific debate around attribution methods, particularly regarding extreme weather events. Attribution is made difficult by high natural variability, the relatively small expected anthropogenic signal, lack of high-quality data, and reliance on deficient climate models. The IPCC has long cautioned that methods to establish causality in climate science are inherently uncertain and ultimately depend on expert judgement.*

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*There are two areas of substantive criticism of the main IPCC assessments of the role of CO<sub>2</sub> in recent warming: focus on inadequate assessment of natural climate variability, uncertainties in measurement of solar variability and aerosol forcing, and problems in the ~~and use of~~ inappropriate statistical methods used for attribution.*

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*The IPCC does not in general make attribution claims for most climate impact drivers related to extreme events.*

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*Attribution of extreme weather events is challenging due to their rarity. The most robust attribution statements for an extreme event relate to an incremental change (eg, a temperature change in degrees or percent change in rainfall). Statements related to statistics of global extremes (eg, event probability (or return times), magnitude and frequency) are not generally considered accurate owing to data limitations and are made with low confidence. Attribution of individual extreme weather events is challenging due to their rarity. Conflicting claims about the causes of the 2021 Western North America Heatwave event provides a good illustration of the perils of making hasty attribution claims about individual extreme events.*

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### 98.1 Introduction

The Intergovernmental Panel on Climate Change (IPCC) distinguishes between detection of climate change and attribution of its cause.<sup>4</sup> As defined by the IPCC AR6 WGI Glossary (IPCC, 2025):

*Detection:* "Detection of change is defined as the process of demonstrating that climate or a system affected by climate has changed in some defined statistical sense, without providing a reason for that change. An identified change is detected in observations if its likelihood of occurrence by chance due to internal variability alone is determined to be small, for example, <10%."

*Attribution:* "Attribution is defined as the process of evaluating the relative contributions of multiple causal factors to a change or event with a formal assessment of confidence."

<sup>4</sup> Note that the IPCC definition of "climate change" allows for both natural and human causes. This differs from the [HYPERLINK "<https://unfccc.int/resource/csite/zimbabwe/conven/text/art01.htm>"] (and common usage), where the term is limited to human causes.

Both steps rely on statistical analysis. Detection focuses on whether changes are significant enough to stand out from random variation regardless of cause. Attribution involves comparison of observed events to model-generated counterfactuals. Since experimentation on the climate is not possible, attribution requires statistical inference to assess how much human activities, such as GHG emissions, versus natural factors, like volcanic eruptions, contribute to observed changes. Attribution methods assume all external and internal drivers of the system are known and represented.

There are ongoing scientific debates around attribution methods, especially those for attributing extreme weather events to climate change. The IPCC has long cautioned that methods to establish causality in climate science are inherently uncertain and ultimately depend on expert judgement. The Fourth Assessment Report: AR4 Working Group I - The Physical Science Basis (Hegerl et al., 2007) explained it as follows:

‘Attribution’ of causes of climate change is the process of establishing the most likely causes for the detected change with some defined level of confidence... unequivocal attribution would require controlled experimentation with the climate system. Since that is not possible, in practice attribution of anthropogenic climate change is understood to mean demonstration that a detected change is ‘consistent with the estimated responses to the given combination of anthropogenic and natural forcing’ and ‘not consistent with alternative, physically plausible explanations of recent climate change that exclude important elements of the given combination of forcings’ (IPCC, 2001)... The approaches used in detection and attribution research described above cannot fully account for all uncertainties, and thus ultimately expert judgement is required to give a calibrated assessment of whether a specific cause is responsible for a given climate change.

The Fifth Assessment Report AR5 Working Group II (Cramer et al., 2014) makes the following statement: (Cramer et al., 2014):

“Two broad challenges to the detection and attribution of climate change impacts relate to observations and process understanding. On the observational side, high-quality, long-term data relating to natural and human systems and the multiple factors affecting them are rare. In addition, the detection and attribution of climate change impacts requires an understanding of the processes by which climate change, in conjunction with other factors, may affect the system in question.”

Because of the complexity of the causal chains in the climate system, investigation of these relationships is exceptionally challenging.

## 98.2 Attribution methods

The Intergovernmental Panel on Climate Change (IPCC) employs several attribution methods to assess the causes of observed climate changes, distinguishing between natural and human-induced factors. Below is a concise description of the key methods that have been used by the IPCC:

*Optimal Fingerprinting* uses linear regression to explain variations in observed climate data as a weighted sum of climate model simulations run with and without anthropogenic forcings. The data used in the regression model are weighted to try to minimize the influence of random noise and the estimation method is chosen to take account of climate model error.

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*Time Series Analysis* exploits statistical differences between anthropogenic forcing and natural variability to see which dominates observed temperatures, and also uses variations in the timing of changes to determine if causal dependence across data series can be inferred.

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*Process-Based Attribution* focuses on understanding the physical mechanisms behind observed changes. This approach combines observations, climate models, and theoretical understanding to attribute changes in specific processes to forcings. This approach is often used for regional climate phenomena, such as monsoon changes or polar amplification

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*Extreme Event Attribution* assesses in the role of human influence in the likelihood of occurrence or intensity of extreme weather events (e.g. heat waves, droughts). Methods include:

- Probabilistic Event Attribution uses large ensembles of climate model simulations to compare observed events to model-generated counterfactuals
- Storyline Approach examines the physical processes driving an event and evaluates how anthropogenic forcings ~~may~~might have modified those processes

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### 98.3 Attribution of global warming

Attribution statements for global warming in the three most recent IPCC Assessment reports are:

AR4: "Most of the observed increase in global average temperatures since the mid-20<sup>th</sup> century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations." (IPCC, 2007)

AR5: "It is *extremely likely* that more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentrations and other anthropogenic forcings together. The best estimate of the human-induced contribution to warming is similar to the observed warming over this period." (IPCC, 2013)

AR6: "The *likely* range of total human-caused global surface temperature increase from 1850–1900 to 2010–2019 is 0.8°C to 1.3°C, with a best estimate of 1.07°C. It is *likely* that well-mixed GHGs contributed a warming of 0.0°C to 0.8°C, other human drivers (principally aerosols) contributed a cooling of 0.0°C to 0.8°C, natural drivers changed global surface temperature by –0.1°C to +0.1°C, and internal variability changed it by –0.2°C to +0.2°C. It is *very likely* that well-mixed GHGs were the main driver of tropospheric warming since 1979." (IPCC, 2021)

The AR4 and AR5 attribution statements reference the warming since the mid-20<sup>th</sup> century, the period when greenhouse gas emissions began rapidly increasing. The words "most" and "more



than half” are deliberately imprecise, potentially ranging from 51 to 99% of the warming – presumably this imprecision is to account for structural uncertainties such as natural internal variability. The confidence level increases from *very likely* to *extremely likely* from AR4 to AR5. The structure of the attribution statement in the AR6 is fundamentally different, referencing the warming to the period 1850-1900. The AR6 attribution statement is more precise numerically, but with a lower level of confidence at “likely” – the AR6 attributes essentially all the warming to increases in greenhouse gases. The most confident statement from the AR6 relates to the tropospheric warming since 1979, using the words “main driver” and “*very likely*.”

There are three areas of substantive criticism of the IPCC’s assessment of the causes of the recent warming: inadequate assessment of natural climate variability, inappropriate statistical methods, and substantial discrepancies between models and observations. The last is discussed in Chapter 6, while this chapter discusses the first two factors. All of these criticisms are relevant to the IPCC’s policy-informing attribution of the recent warming, which also underpins extreme event attribution

### 98.3.1 Natural climate variability

IPCC AR6 states that natural external drivers since 1850-1900 have changed global surface temperature by  $-0.1^{\circ}\text{C}$  to  $+0.1^{\circ}\text{C}$ , and internal variability has changed it by  $-0.2^{\circ}\text{C}$  to  $+0.2^{\circ}\text{C}$  – on average having essentially no net impact on the warming since 1850-1900. ~~As discussed below, this minimal contribution of natural variability has been disputed by a number of several publications that question the magnitudes of solar variability and internal variability from the large-scale ocean circulations (R Connolly et al., 2021; W Soon, 2023).~~

~~If the Equilibrium Climate Sensitivity to  $\text{CO}_2$  is low (Chapter 5), then natural climate variability becomes more important in the attribution of the recent warming. Further, if natural variability is higher, then estimates of the Equilibrium Climate Sensitivity from the historical period would be lower (Seafetta 2023).~~

### Solar variability

IPCC AR5 concluded that the best estimate of radiative forcing due to Total Solar Irradiance (TSI) changes over the period 1750–2011 was very small ( $0.05 \text{ W/m}^2$ ) (Myrhe et al., 2014). IPCC AR6 acknowledges a much larger range of estimates of changes in TSI over the last several centuries, stating that the TSI between the Maunder Minimum (1645–1715) and the second half of the twentieth century increased by  $0.7\text{--}2.7 \text{ W/m}^2$ , a range that includes both low and high variability TSI data sets (Gulev, 2021). However, the recommended forcing dataset for the CMIP6 climate model simulations used in AR6 for attribution studies averages two data sets with low solar variability (Matthes, 2017).

While AR6 shows a substantially greater solar impact than does AR5, the overall impact on the climate was still assessed to be small compared to anthropogenic forcing of climate change. However, the impact of solar variations on the climate is uncertain and subject to substantial debate – something that is not evident from the IPCC assessment reports (Lockwood, 2012; Connolly et al., 2021).

~~The change of Exactly how TSI over time has changed over time has been remains a challenging~~

problem. ~~to resolve.~~ Since 1978, there have been direct measurements of TSI from satellites. However, the data ~~exhibit~~exhibits non-negligible inconsistencies, and interpreting any multi-decadal trends in TSI requires comparisons of observations from overlapping satellites. There are several rival composite TSI datasets, disagreeing as to whether TSI increased or decreased during the period 1986–96 (the ACRIM gap; see Chapter 4). Further, the satellite record of TSI is used ~~for calibrating to~~ calibrate proxy models, whereby past solar variations are inferred from sunspots and cosmogenic isotope measurements (Velasco Herrera et al., 2015).

There is substantial evidence for high solar activity in the second half of the 20<sup>th</sup> century (starting in 1959) and extending into the 1990's, before a decline in the early 21<sup>st</sup> century; this period is often termed the “Modern Maximum.” (Chatzistergos et al., 2023; Solanki et al., 2004; Usoskin et al., 2007). However, some scientists have concluded that it is not possible to be confident of any multi-decadal trend in TSI (Schmutz, 2021).

~~As a result of this~~ this uncertainty causes, some reconstructions for past values of TSI (since from 1750) to have low variability, (implying a very low impact of solar variations on global mean surface temperature), whereas datasets with high TSI variability can explain more than 70% percent of the temperature variability since preindustrial times (Scafetta, 2013; Stefani, 2021). ~~Hence, the~~ The choice of which TSI satellite record used in an analysis can therefore substantially influence how much climate change is attributed to human versus natural forcings.

There is growing evidence that other aspects of solar variability, which are referred to as solar indirect effects, either amplify TSI forcing or are independent of TSI forcing. Scafetta et al. (2023) suggests that ~80% of solar influence on climate may stem from non-TSI mechanisms. ~~There are numerous candidate candidate processes, including include:~~ solar ultraviolet changes; energetic particle precipitation; atmospheric-electric-field effect on cloud cover; cloud changes produced by solar-modulated galactic cosmic rays; large relative changes in the magnetic field; and the strength of the solar wind. ~~Such solar indirect effects are not included in climate models, although indirect methods of estimating these effects their impacts suggest they are significant influence.~~ However, claims of non-TSI mechanisms influencing climate are uncertain and debated.

#### *Natural variability of large-scale ocean circulations*

Variations in global mean surface temperature are linked to recurrent large-scale variations in ocean circulation patterns, ~~including. These circulation patterns include~~ the Atlantic Multidecadal Oscillation (AMO), the Pacific Decadal Oscillation (PDO) and the El Niño-Southern Oscillation (ENSO). These circulations ~~patterns influence~~ ocean heat uptake and heat distribution, and also influence atmospheric circulation patterns and cloud distributions. There is some debate as to whether these variations are strictly internal to the climate system, or whether this variability can have a solar/astronomical origin or can be influenced by large volcanic eruptions.

While climate models simulate the large-scale ocean circulations and internal climate variability, ~~most models show too little power relative to observations at the simulated magnitude in the multi-decadal band frequencies is too low in most models relative to observations, and the phasing of the variability in long-term climate simulations is not phasing out of sync with the actual, observed climate variations.~~ (Kravtsov et al. 2024). Averaging multiple simulations from climate models effectively averages out the internal variations, leaving only the forced climate variability

(e.g., CO<sub>2</sub> forcing). With most of the modern warming beginning in the late 1970's, the recent 50-year warming is on the same time scale as the multi-decadal oscillations of the AMO and PDO.

Here are summary statements from the IPCC AR5 and AR6 reports:

"Decadal variability in the Pacific, associated with the PDO or IPO [Interdecadal Pacific Oscillation], contributes significantly to regional and global temperature trends, but the relative contributions of internal variability and external forcing are difficult to disentangle in CMIP5 simulations." (IPCC, 2013)

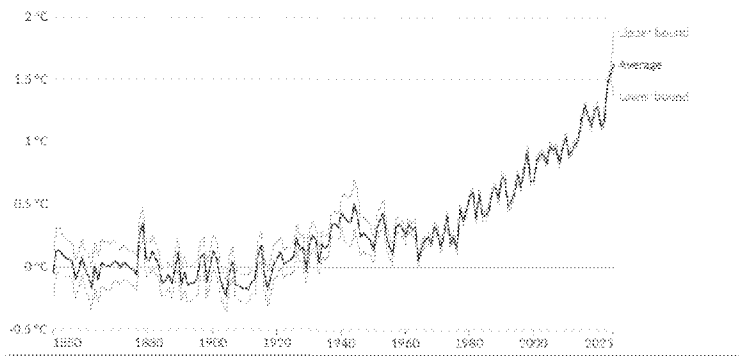
"Since AR5, there has been increased understanding of the role of internal variability, such as ENSO, PDO, and AMO, in modulating regional climate trends. However, limitations in simulating the exact timing and amplitude of these modes in CMIP6 models contribute to uncertainties in attributing observed changes to anthropogenic forcing (high confidence)." (IPCC, 2021)

The amplitude of the peak-to-trough impact of the multi-decadal oscillations on global temperatures has been assessed by the IPCC AR6: "The likely range of change due to internal variability is -0.2°C to +0.2°C (IPCC, 2021)." This implies a trough-to-peak change of 0.4°C. Over many centuries, any global temperature changes from the troughs and peaks will cancel out, with little to no net impact.

However, with a nominal timescale of 60-80 years for oscillations such as the AMO and PDO, the timing of the peaks and troughs can be confused with the secular trend. This becomes very relevant for attributing the warming for the past 50 years, when most of since 1975, during which most of the recent warming has occurred. Even if climate models have the correct amplitude of the multidecadal oscillations, the timing of the peaks and troughs is not adequately simulated, with each model and individual ensemble simulating a different phasing. Once the simulations of the ensemble members and different models are averaged, the natural internal variability contribution is averaged out, effectively cancelling the role of natural internal variability in the attribution process.

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**Figure 8.1** Global average surface temperature.

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The Great Pacific Climate Shift of 1976-1977 was a notable climatic event characterized by an abrupt change in the North Pacific Ocean's atmosphere-ocean system that interacted with global climate patterns. This shift is closely associated with the Pacific Decadal Oscillation (PDO) that oscillates between warm and cool phases over decades. The 1976 shift marked a transition from a predominantly negative (cool) PDO phase (1947-1976) to a positive (warm) phase (1977 through 2000), with significant implications for global and regional climate patterns including the frequencies of El Niño and La Niña events. The Great Pacific Climate Shift coincided with the beginning of a period of accelerated global warming. ~~(REF TO A FIG OF GLOBAL TEMP ANOMALIES ELSEWHERE IN DOC)~~ When the Great Pacific Climate Shift is accounted for in climate attribution analyses since 1950, ~~it has been found that 40 percent or more of the warming in the second half of the 20<sup>th</sup> century was caused by~~ is attributed to natural internal variability (McLean et al, 2009; Tung and Zhou, 2013; Chylek et al, 2016; Safetta, 2021).

### 98.3.2 *Optimal fingerprinting*

Optimal fingerprinting is a statistical technique introduced by Allen and Tett (1999) that compares observed climate data to climate model simulations to identify patterns (or "fingerprints") associated with human or natural forcing. It involves taking a vector of observed climate changes, such as warming rates in locations around the world, and decomposing them into a weighted sum of "signals", which are analogues to the observations generated by climate models with different types of forcings. The weights are chosen using a regression method called Total Least Squares. The analysis commonly uses just two signals, one generated by models using only anthropogenic forcings and one using only natural forcings. If the estimated weighting coefficient attached to a signal is significantly different from zero, then that signal is said to be "detected". If it is close to 1.0, then the model generating the signal is said to be consistent with observations. If it is less than 1.0, then the model signal for that forcing is too strong and needs to be scaled down, and vice-versa. Both the observed data and the signals are weighted using a model-generated estimate of patterns of randomness in the climate system so as, in principle, to put maximum weight on regions where natural variability is minimized.

Optimal fingerprinting is the primary tool for attribution in the climate research literature. While it has been widely used and prominently featured by the IPCC since 2001 there is very little literature examining the statistical properties of the results it generates. Studies applying it have been cited thousands of times, and it has been prominently featured by the IPCC since the 2001 Third Assessment Report. One of its inherent weaknesses is that results depend on assumptions about the accuracy of climate models, especially regarding their representation of natural variability (IPCC AR5 Ch 10.2.3).

Additionally, a series of papers by McKittrick (McKittrick 2022a, 2022b, 2023, 2025) has challenged the optimal fingerprinting method, arguing that it is inherently unreliable and that commonly used practices adapted from econometrics can provide more valid results. Statistical theory requires that for regression models to yield unbiased coefficients, a set of assumptions called the Gauss-Markov conditions must hold. McKittrick (2022a) argued that the Allen and Tett (1999) methodology violates the Gauss-Markov conditions, leading to potentially biased and inconsistent fingerprinting coefficients, undermining the reliability of the method. Chen et al (2023) confirmed this analysis and argued that the method could yield unbiased results but only under very stringent assumptions. McKittrick (2022b) and (2023) raised a further concern that climate scientists—virtually alone among scientific disciplines—have used an estimation method called Total Least Squares (TLS) to estimate anthropogenic greenhouse gas signal coefficients, despite its tendency to be unreliable unless some strong assumptions hold that in practice are unlikely to be true. Under conditions which ~~that~~ easily arise in optimal fingerprinting, TLS yields estimates with large positive biases. Thus, any study that has used TLS for optimal fingerprinting without verifying that it is appropriate and applicable in the specific data context has likely overstated the result.

McKittrick (2025) presented an empirical example comparing the results of conventional optimal fingerprinting against methods drawn from mainstream econometrics which ~~that~~ are known to be valid for the specific application of signal detection. While the IPCC optimal fingerprinting method yields an anthropogenic signal coefficient close to 1.0 on a global temperature data set spanning 1900 to 2010, consistent estimation yields a coefficient around 0.4, which rises to about 0.65 on data spanning 1980 to 2010, implying the model response to greenhouse gases needs to be scaled down by about half to optimally match observations. The natural forcing signal coefficient, by contrast, is between 2.0 and 4.0, implying the climate model signals of natural forcing need to be scaled up two-to-four-fold to match observed climate change. The fingerprinting coefficients estimated in McKittrick (2025), when used to scale the average sensitivity of the climate models used to generate the forcing signals in his data set, imply a Transient Climate Sensitivity of 1.4°C, which ~~matches~~ is consistent with the estimate by Lewis (2022) using a different estimation method and multiple independent data sets.

While these analyses do not prove that ~~all of the~~ results from stemming from using the IPCC optimal fingerprinting method ~~are wrong~~, it does ~~they do~~ challenge ~~show~~ that the basis on which they were believed to be correct ~~is non-existent~~—hence reducing confidence in the results.

### **98.3.3 Time series methods**

The IPCC (AR5 WGI 10.2.2) drew attention to alternative approaches of assessing causality that emerged from the time series econometrics literature. ~~They~~ These have the advantage of not depending on assumptions about the accuracy of climate models, but ~~then~~ the disadvantage is

that they depend on difficult-to-test assumptions about the data generating process underlying climate and forcing data, that are not straightforward to test. The methods, now referred to as climate econometrics, use the tools of unit root testing, Granger causality and cointegration analysis, all of which are familiar in economics and finance and which are slowly being adopted in climate science. Time series analysis methods hold out the possibility of determining whether anthropogenic or natural forcings are the primary drivers of climate change without requiring the use of climate models, although key questions remain unsettled (e.g. Dergiades et al. 2016, Balcombe et al. 2019, Dagsvik et al. 2020, Razzak 2022, Dagsvik and Moen 2023).

“Granger causality” modeling is a tool for determining directions of influence in data series that move together. “Granger causality” is a statistical, not a physical, concept. If knowing the current value of one variable significantly improves the forecast accuracy of another variable we can infer a causal connection exists; this is called Granger causality. The modeling tools, called vector autoregression, measure direct impulse-response patterns and feedbacks. An application to the well-known Vostok ice core data revealed an error by Al Gore in his Al Gore’s documentary *An Inconvenient Truth*. Gore showed the data and drew attention to the coherence of temperature and CO<sub>2</sub> changes over a 440,000 year span, which he asserted was due to CO<sub>2</sub> driving temperature changes. But temperature changes can also affect atmospheric CO<sub>2</sub> levels. Davidson et al. (2015) examined the series and found that temperature Granger causes CO<sub>2</sub> but not the reverse. In other words on the time scales represented in the Vostok data the coherence in the series is primarily due to the influence of temperature on CO<sub>2</sub> levels not the feedback going from CO<sub>2</sub> levels to temperature.

In summary, the main primary statistical methods for attributing causation in climate data are optimal fingerprinting and time series analysis. Applications of the Allen and Tett (1999) optimal fingerprinting method dominate the attribution literature and have underpinned past IPCC conclusions, but results depend on the accuracy of climate models and the method has recently been criticized as inherently biased. Time series methods do not depend on climate models but require assumptions of their own and have generated results that have thus far not converged on a consensus.

#### 8.4 Declining planetary albedo and recent record warmth

A sharp recent increase in global average temperatures has raised the question of short-term drivers of climate. One such candidate is the fraction of absorbed solar radiation which has also changed abruptly in recent years. The question to be answered is whether the change is an internal feedback to warming caused by greenhouse gases or whether something else changed the fraction of absorbed radiation which then caused the recent warming.

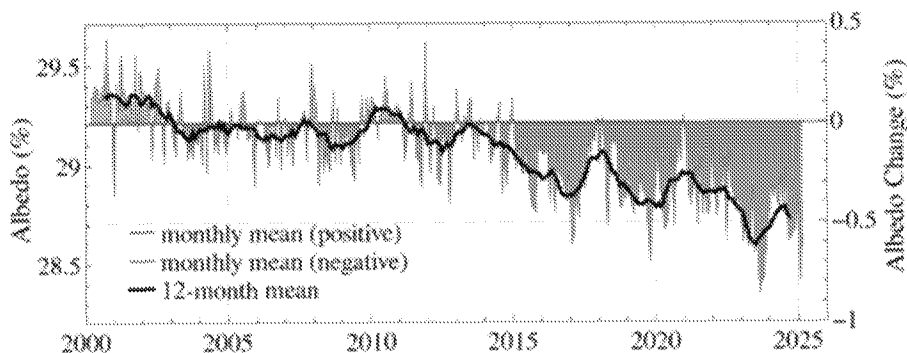
The albedo is the fraction of incoming solar radiation that is reflected back into space rather than being absorbed by the planet. Highly reflective surfaces like cloud tops and snow and ice are most important in this regard. The Earth’s albedo is approximately 30%, meaning almost a third of the sunlight that reaches Earth is directly reflected back to space. A lower albedo implies more solar energy is absorbed by the planet to be then re-radiated as heat. Hence, other things being equal, a decline in albedo is associated with a warming of the Earth.

Arguably the most striking change in the Earth’s climate system during the 21<sup>st</sup> century is a significant reduction in planetary albedo since 2015, which has coincided with at least two years of record global

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warmth. Figure 8.1 shows the planetary albedo variations since 2000, when there are good satellite observations. The 0.5% reduction in planetary albedo since 2015 corresponds to an increase of  $1.7 \text{ W/m}^2$  in solar energy averaged over the planet (Hansen and Karocha, 2025). For comparison, the IPCC estimate of forcing from the increase in atmospheric  $\text{CO}_2$  compared to preindustrial times is approximately  $2.2 \text{ W/m}^2$  (Figure 3.1.2).

Looking back prior to 2000 with less adequate data, Gossling et al. (2025) assessed that planetary albedo was relatively low around the 1940's and 50's, before rising industrial aerosol precursor emissions increased albedo until the 1980's. The strongest planetary albedo excursions were high-albedo episodes caused by volcanic eruptions, such as after the Mount Pinatubo eruption in 1991. Although uncertain, the 2023 planetary albedo minimum may have been the lowest since at least 1940.



**Figure 8.1.** Earth's albedo (reflectivity, in percent), with seasonality removed. From Hansen and Karocha (2025)

Changes in surface characteristics can't explain this decrease in planetary albedo since 2015:

- Arctic sea ice extent has declined by about 5% since 1980 ([https://nsidc.org/data/seaice\\_index/images/s\\_plot\\_hires.png](https://nsidc.org/data/seaice_index/images/s_plot_hires.png)), although following 2007 there has been a pause in the Arctic sea ice decline (England et al., 2025)
- Regarding Antarctic sea ice, the IPCC AR6 concludes that "There has been no significant trend in Antarctic sea ice area from 1979 to 2020 due to regionally opposing trends and large internal variability." (SPM, A.1.5)
- Northern hemispheric annual snow cover has been slowly declining since 1967, with barely significant trends. The data show the Northern Hemisphere has snowier winters, accompanied by more rapid melt in spring and summer. [HYPERLINK "<http://climate.rutgers.edu/snowcover/>"]
- Global greening (Chapter 2) is contributing to the decrease in planetary albedo, as forests have a lower albedo than open lands or snow. However, there is some evidence that forests increase cloud cover (high reflectivity), which counteracts the direct albedo increase associated with increasing forested area.

Changes in surface reflectivity are contributing to a small, slow decline in planetary albedo. However, these changes cannot explain the sharp decline in planetary albedo beginning in 2015. Further, any changes in surface albedo are effectively damped by about a factor 3 on average, primarily due to cloud

masking (Loeb et al. 2019). Surface albedo changes have thus contributed only weakly to the recent planetary albedo decline, particularly when averaged annually and globally.

This leaves the most likely explanation for the sharp albedo decline as changes in atmospheric aerosols and/or clouds.

Aerosols are small particles in the atmosphere that reflect sunlight and can interact with cloud processes to make the clouds more reflective. Aerosols have both natural origins (e.g. dust from soils, wildfires) as well as human origins from combustion (including fossil fuels). Regions that are greening and/or have an increase in rainfall may be producing less dust. For anthropogenic aerosols, new ship fuel regulations aimed at reducing sulfur emissions were implemented in three phases, in 2010, 2015 and 2020. Sulfate particles reflect solar radiation. Cleaner air means less solar radiation is reflected, which contributes to surface warming. Indirect effects of sulfate aerosols include increasing the reflectivity of low-level clouds in the subtropics. There is controversy surrounding the importance of this change in sulfate emissions to the Earth's radiation balance (Hodnebrog et al., 2024; Yuan et al., 2024), but the restriction of this effect to major shipping routes suggests a small global impact (Schmidt, 2024).

This leaves changes in clouds as the primary candidate to explain the decline in global albedo since 2015. Two recent papers (Loeb et al., 2024; Gosling et al. 2024) have addressed recent variations in cloud properties. By considering satellite and reanalysis data, Loeb et al. found that decreases in low and mid-level clouds since 2015 are the primary reason for decreasing planetary albedo in the Northern hemisphere, whereas in the Southern hemisphere the decrease in planetary albedo is primarily due to decreases in mid-level clouds across all latitude zones. Gosling et al. (2025) found that cloud anomalies were mainly due to reduced low-level clouds. Regions with coherent low-level cloud reductions over the past decade include the warm pool region around the Maritime Continent and the northern extratropical western Pacific, as well as large parts of the Atlantic and adjacent land regions. The reduction of global cloud cover identified in these analyses since 2015 is 1-2 percent.

The question then becomes what caused the change in cloud cover. Two causes have been posited for the declining cloud cover over the past decade:

- Natural climate variability
- Changes in low cloud cover associated with warming sea surface temperatures, implying an emerging positive feedback to climate change (Hansen and Karecha, 2025)

The existence of a new positive low cloud feedback that began emerging in 2015 is not easy to justify. However, there are numerous natural climate signals during this period that are associated with atmospheric circulation changes that can influence the distribution of clouds:

- The 2014-2016 was the strongest El Niño event on record
- A cold anomaly beginning in 2015 in the subpolar gyre of the North Atlantic reflects a shift in the ocean circulation pattern associated with decadal variability in the Atlantic (Frajka-Williams et al., 2017; Arthun et al. 2021).
- The Pacific Decadal Oscillation (PDO) positive index peaked in 2016, then declined and has been in negative territory since late 2019
- Eruption of the submarine Hunga-Tonga volcano in 2022

Interannual cloud anomalies associated with the El Niño Southern Oscillation (ENSO) have a significant global signal and strong regional signals especially over the tropical Indian and Pacific Oceans.

The Hunga Tonga eruption is remarkable in its coincidence with the exceptionally low value of planetary albedo in 2023. Gosling et al. (2025) found that the cloud perturbations in 2023 showed a different



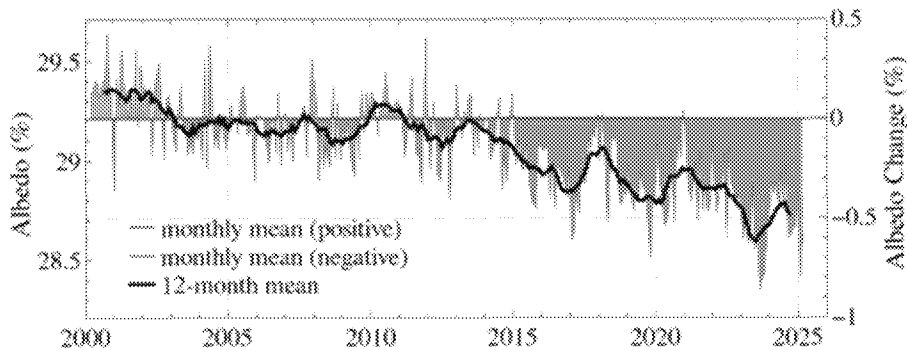
pattern from the overall pattern since 2015, with reduced cloud cover being most pronounced in the northern hemisphere and tropics. Regional reductions in cloud cover were most pronounced over the eastern Indian Ocean, over South America and extending over the eastern Pacific, as well as over northern North America, in the Southern Ocean around 60S, in the subtropical and eastern North Atlantic, and in parts of the North Pacific.

The Hunga Tonga eruption was unusual in that it injected large amounts of water vapor into the stratosphere, in addition to sulfate particles. Early publications focused on the impacts to stratospheric circulations and the direct radiative impact. In 2025, papers are emerging that examine the indirect effects of Hunga Tonga on surface climate using ensemble simulations from earth system models (Bednarczyk et al. 2025; Kuchar et al., 2025). These papers found statistically significant impacts on regional climates that were driven by circulation changes from couplings between the stratosphere and troposphere. These papers indicate the complex interactions between volcanic activity and climate dynamics. More research is needed to untangle any impacts of Hunga Tonga eruption on planetary albedo.

In summary, the decline in planetary albedo and the concurrent decline in cloudiness have emphasized the importance of clouds and their variations to global climate variability and change. A change of 1 to 2 percent in global cloud cover has a greater radiative impact on the climate than the direct radiative effect of doubling CO<sub>2</sub>. While it is difficult to untangle causes of the trend the competing explanations for the cause of the declining cloud cover have substantial implications for assessing the Equilibrium Climate Sensitivity and also the attribution of the recent warming. An additional 10 years of data should help clarify whether this is a strong positive cloud feedback associated with warming, or a temporary fluctuation driven by natural variability.

Planetary albedo is the fraction of incoming solar radiation that is reflected back into space by reflective surfaces like cloud tops and snow rather than being absorbed at the surface. Earth's planetary albedo is approximately 30%, meaning almost a third of the sunlight that reaches Earth is directly reflected back to space. A lower albedo implies more solar energy is absorbed at the surface to be then re-radiated as heat into the atmosphere. Hence, other things being equal, a decline in Earth's albedo is associated with a warming of the atmosphere.

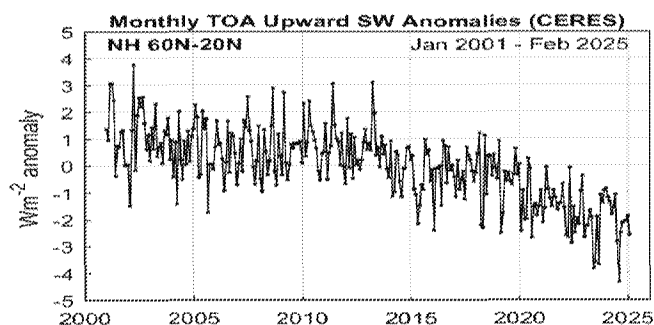
Arguably the most striking change to the Earth's climate system in the 21<sup>st</sup> century is a significant reduction in planetary albedo since 2015, which has coincided with record global warmth. Figure 8.1 shows the planetary albedo variations since 2000, when we have good satellite observations. The 0.5% reduction in planetary albedo since 2015 corresponds to a 1.7 W/m<sup>2</sup> increase of solar energy averaged over the planet (Hansen and Karstedt, 2025). For reference, doubling of CO<sub>2</sub> has a direct radiative impact of about 1.2 W/m<sup>2</sup>.



**Figure 8.1** Earth's albedo (reflectivity, in percent), with seasonality removed. From Hansen and Karacki (2025)

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The regional decline since 2015 is even more striking for the latitude band 20N to 60N. Figure 8.2 shows the upward (reflected) solar flux anomaly at the top of atmosphere (TOA), as determined from the CERES satellite analysis.



**Figure 8.2** Upward (reflected) solar flux anomaly at the top of atmosphere (TOA), as determined from the CERES satellite analysis. <https://ceres.larc.nasa.gov/data/>

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Looking back prior to 2000 with less adequate data, Gosling et al. (2025) assessed that planetary albedo was relatively low around the 1940's and 50's, before industrial aerosol precursor emissions led to global dimming until the 1980's. The strongest planetary albedo excursions were high-albedo episodes caused by volcanic eruptions, such as after the Mount Pinatubo eruption in 1991. Although uncertain, the 2023 planetary albedo minimum may have been the lowest since at least 1940.

Changes in surface characteristics can't explain this decrease in planetary albedo since 2015:

----- Arctic sea ice extent has declined by about 5% since 1980

([https://nsidc.org/data/seaice\\_index/images/s\\_plot\\_hires.png](https://nsidc.org/data/seaice_index/images/s_plot_hires.png)), although following 2007 there has been a pause in the Arctic sea ice decline (England et al., 2025)

- Regarding Antarctic sea ice, the IPCC AR6 concludes that “There has been no significant trend in Antarctic sea ice area from 1979 to 2020 due to regionally opposing trends and large internal variability.” (SPM, A.1.5)
- Northern hemispheric snowcover has been slowly declining since 1967, with barely significant trends. The data show the Northern Hemisphere has snowier winters, accompanied by more rapid melt in spring and summer.  
[HYPERLINK "<http://climate.rutgers.edu/snowcover/>"]
- Global greening (Chapter 2) is contributing the decrease in planetary albedo, as forests have a lower albedo than open lands or snow. However, there is some evidence that forests increase cloud cover (high reflectivity), which counteracts the direct albedo increase associated with increasing forested area.

Changes in surface reflectivity are contributing to a small, slow decline in planetary albedo. However, these changes cannot explain the sharp decline in planetary albedo beginning in 2015. Further, any changes in surface albedo are effectively damped by about a factor 3 on average, primarily due to cloud masking (Loeb et al. 2019). Surface albedo changes have thus contributed only weakly to the recent planetary albedo decline, particularly when averaged annually and globally.

This leaves the most likely explanation for the sharp albedo decline as being caused by changes in atmospheric aerosols and/or clouds.

Aerosols are small particles in the atmosphere that reflect sunlight and can interact with cloud processes to make the clouds more reflective. Aerosols have both natural origins (e.g. dust from soils, wildfires) as well as human origins from combustion (including fossil fuels). Regions that are greening and/or have an increase in rainfall may be producing less dust. In terms of pollution aerosol, new ship fuel regulations aimed at reducing sulfur emissions were implemented in three places, in 2010, 2015 and 2020. Sulfate particles reflect solar radiation. Cleaner air means less solar radiation is reflected, which contributes to surface warming. Indirect effects of sulfate aerosols include increasing the reflectivity of low-level clouds in the subtropics. There is controversy surrounding the importance of this change in sulfate emissions to the Earth's radiation balance (Hodnebrog et al., 2024; Yum et al., 2024), but the restriction of this effect to major shipping routes suggests a small global impact (Schmidt, 2024).

This leaves changes in clouds as the primary candidate to explain the decline in global albedo since 2015. Loeb et al. (2024) and Goching et al. (2024) have addressed recent variations in cloud properties. By considering satellite and reanalysis data, Loeb et al. found that decreases in low and mid-level clouds since 2015 are the primary reason for decreasing planetary albedo in the northern hemisphere, whereas in the southern hemisphere the decrease in planetary albedo is primarily from decreases in mid-level clouds across all latitude zones. Goching et al. (2025) found that cloud anomalies were mainly due to reduced low-level clouds. Regions with coherent low-level cloud reductions over the past decade include the warm pool region around the Maritime Continent and the northern extratropical western Pacific, as well as large parts of the Atlantic and adjacent land regions. The reduction of global cloud cover identified in these analyses since 2015 is 1.2 percent.

Two causes have been posited for the declining cloud cover over the past decade:

- Natural climate variability
- Changes in low cloud cover associated with warming sea surface temperatures, implying an emerging positive feedback to climate change (Hansen and Karecha, 2025)

The existence of a new positive low cloud feedback that began emerging in 2015 is not easy to justify. However, there are numerous natural climate signals during this period that are associated with atmospheric circulation changes that can influence the distribution of clouds:

- The 2014–2016 was the strongest El Niño event on record
- A cold anomaly beginning in 2015 in the subpolar gyre of the North Atlantic reflects a shift in the ocean circulation pattern associated with decadal variability in the Atlantic (Frajka-Williams et al., 2017; Arthun et al. 2021).
- The Pacific Decadal Oscillation (PDO) positive index peaked in 2016, then declined and has been in negative territory since late 2019 <https://www.ncei.noaa.gov/access/monitoring/pdo/>
- Eruption of the submarine Hunga Tonga volcano in 2022

Interannual cloud anomalies are associated with the El Niño Southern Oscillation (ENSO), which have a significant global signal and strong regional signals especially over the tropical Indian and Pacific Oceans

The Hunga Tonga eruption is remarkable in its coincidence with the exceptionally low value of planetary albedo in 2023. Gosling et al. (2025) found that the cloud perturbations in 2023 showed a different pattern from the overall pattern since 2015, with reduced cloud cover being most pronounced in the northern hemisphere and tropics. Regional reductions in cloud cover were most pronounced over the eastern Indian Ocean, over South America, and extending over the eastern Pacific, as well as over northern North America, in the Southern Ocean around 60S, in the subtropical and eastern North Atlantic, and in parts of the North Pacific.

The Hunga Tonga eruption was unusual in that it injected large amounts of water vapor into the stratosphere, in addition to sulfate particles. Early publications focused on the impacts to stratospheric circulations and the direct radiative impact. In 2025, papers are emerging that examine the indirect effects of Hunga Tonga on surface climate using ensemble simulations from earth system models (Bednarz et al. 2025; Kuchar et al. 2025). These papers found statistically significant impacts on regional climates that were driven by circulation changes from couplings between the stratosphere and troposphere. These papers indicate the complex interactions between volcanic activity and climate dynamics. More research is needed to untangle any impacts of Hunga Tonga eruption on planetary albedo.

In summary, the decline in planetary albedo and the concurrent decline in cloudiness have emphasized the importance of clouds and their variations to global climate variability and change. A change of 1 to 2 percent in global cloud cover has a greater radiative impact on the climate than the direct radiative effect of doubling CO<sub>2</sub>. It is difficult to untangle causes of the recent decline in planetary albedo without adequate data in the 20<sup>th</sup> century. However, the two competing explanations for the cause of the declining cloud cover have substantial implications for assessing the Equilibrium Climate Sensitivity and also the attribution of the recent warming. An additional 10 years of data should help clarify whether this decline is caused by a strong positive cloud feedback associated with warming or a temporary fluctuation driven by natural variability.

#### 98.4.5 Attribution of climate impact drivers

The IPCC (Ranasinghe et al. 2021) defines “climate impact drivers” or CIDs as “physical climate system conditions (e.g., means, events, extremes) that affect an element of society or ecosystems.” Hence CIDs are those features of the weather and climate system of primary interest when assessing the impacts of climate change since they potentially affect humans and the natural world. For instance, under the heading “Heat and Cold” CIDs are identified as mean air temperature, extreme heat, cold spells and frost. The IPCC also points out that CIDs are not necessarily harm-related: depending on the system in question they can be detrimental, neutral, beneficial or a combination.

| The first column of Table 12.12 in Ranasinghe et al. (2021, p. 1856), reproduced here as Table 98.1, summarizes the AR6 assessment of whether a signal of attributable anthropogenic influence has emerged across all major CIDs. One of the themes of this chapter is that attribution methods used by the IPCC tend to overstate the anthropogenic influence and understate the role of natural variability. Nonetheless a striking feature of that summary table is how few CIDs exhibit an anthropogenic signal sufficient to distinguish them from natural variability.

| Climatic impact-driver type | Climatic impact-driver Category        | Already Emerged in Historical Period |
|-----------------------------|----------------------------------------|--------------------------------------|
| Heat and Cold               | Mean air temperature                   | 1                                    |
|                             | Extreme heat                           | 2                                    |
|                             | Cold spell                             | 4                                    |
|                             | Frost                                  |                                      |
| Wet and Dry                 | Mean precipitation                     |                                      |
|                             | River flood                            |                                      |
|                             | Heavy precipitation and pluvial flood  |                                      |
|                             | Landslide                              |                                      |
|                             | Acidity                                |                                      |
|                             | Hydrological drought                   |                                      |
|                             | Agricultural and ecological drought    |                                      |
|                             | Fine weather                           |                                      |
| Wind                        | Mean wind speed                        |                                      |
|                             | Severe wind storm                      |                                      |
|                             | Tropical cyclone                       |                                      |
|                             | Sand and dust storm                    |                                      |
| Snow and Ice                | Snow, glacier and ice sheet            |                                      |
|                             | Permafrost                             |                                      |
|                             | Lake, river and sea ice                | 11                                   |
|                             | Heavy snowfall and ice storm           |                                      |
|                             | Hail                                   |                                      |
|                             | Snow avalanche                         |                                      |
| Coastal                     | Relative sea level                     |                                      |
|                             | Coastal flood                          |                                      |
|                             | Coastal erosion                        |                                      |
| Open Ocean                  | Mean ocean temperature                 |                                      |
|                             | Marine heatwave                        |                                      |
|                             | Ocean acidity                          |                                      |
|                             | Ocean salinity                         | 13                                   |
|                             | Dissolved oxygen                       | 14                                   |
| Other                       | Air pollution weather                  |                                      |
|                             | Atmospheric CO <sub>2</sub> at surface |                                      |
|                             | Radiation at surface                   |                                      |

|                             |                               |                                       |                               |                             |
|-----------------------------|-------------------------------|---------------------------------------|-------------------------------|-----------------------------|
| High confidence of decrease | Medium confidence of decrease | Low confidence in direction of change | Medium confidence of increase | High confidence of increase |
|-----------------------------|-------------------------------|---------------------------------------|-------------------------------|-----------------------------|

**Table 98.1:** Reproduction of column 1 of Table 12.12, IPCC AR6 Working Group I report. Emergence of anthropogenic signal in historical period for CIDs shown. White: no signal detected. Blue and orange: change detected (decrease or increase) and confidence level as indicated in color legend.

Out of the 33 weather impact categories an anthropogenic signal is asserted with *high confidence* in only five, and with *medium confidence* in a further four. (Note that one of the CIDs is an increase in CO<sub>2</sub> levels, and since it is a tautology to attribute this to increased CO<sub>2</sub> levels this CID can be ignored.) For the rest the IPCC does not claim to have detected anthropogenic drivers. Of the five *high confidence* assertions, two are for changes in average temperatures (air and ocean) hence are not measures of extreme weather. Also two of the four *medium confidence* assertions are related to ocean chemistry and thus are likewise not related to extreme weather. The IPCC does not assert a human influence on many non-temperature weather features such as wind, precipitation, flooding, drought etc

Columns 2 and 3 of IPCC Table 12.12 report on whether anthropogenic signals are expected to emerge this century under RCP8.5, the most extreme forcing scenario. We have omitted these columns for several reasons. First, in part because they refer to whether climate models project detectable signals will be detectable in the data observations, but this which is a very different question than the one that concerns us here, namely our concern here whether a signal has been detected in historical data. Second, Additionally, as we discuss in Chapter 4, the RCP8.5 scenario is a misleading and implausible high-end storyline, it is not a “base case” or business-as-usual projection. Third, the ensemble of detailed models is acknowledged (Palmer, 2019) to be “not fit for purpose” in describing regional changes and “unable to represent future conditions at the degree of spatial, temporal and probabilistic precision with which projections are often provided.” (Nissan, 2019) Even with these caveats, Even still it is worth noting we note that the omitted columns in AR6 Table 12.12 indicate most weather impacts are not expected to exhibit an anthropogenic signal this century.

As we discussed in Chapter 7 natural variability dominates patterns of extreme weather systems and simplistic assertions of trend detection are frequently undermined by regional heterogeneity and trend reversals over time. Table 98.1 makes the related point that, again contrary to popular belief, attribution of changes in most extreme weather types to human influence is not currently possible. Taking wind as an example, the IPCC claims that an anthropogenic signal has not emerged in average wind speeds, severe windstorms, tropical cyclones or sand and dust storms, nor is one expected to emerge this century even under an extreme emissions scenario. The same applies to drought and fire weather.

Citations Palmer [HYPERLINK "<https://www.pnas.org/doi/full/10.1073/pnas.1906691116>"]  
Nissan [HYPERLINK "<https://wires.onlinelibrary.wiley.com/doi/10.1002/wcc.579>"]

#### 98.5-6 Extreme event attribution (EEA)

Examining the IPCC's treatment of extreme weather and climate event attribution more broadly, the AR6 provides an ambiguous assessment of the role of anthropogenic warming that differs between chapters. Chapter 11 of WG1 states (Seneviratne et al, 2021):

“Evidence of observed changes in extremes and their attribution to human influence (including greenhouse gas and aerosol emissions and land-use changes) has strengthened since AR5, in particular for extreme precipitation, droughts, tropical cyclones and compound extremes (including dry/hot events and fire weather). Some recent hot extreme events would have been extremely unlikely to occur without human influence on the climate system.”

By contrast, as noted above, Chapter 12 of WG1 (Table 12.12) paints a different picture – presumably, the expert judgment of different groups of authors for the two chapters came to different conclusions (Ranasinghe, 2021):

- High confidence in an increase in extreme heat events in tropical regions where observations allow trend estimation and in most regions in the mid-latitudes, medium confidence elsewhere
- Medium confidence in a decrease in extreme cold events in Australia, Africa and most of northern South America where observations allow trend estimation
- No evidence of emergence in the historical period of a change in river floods, heavy precipitation, drought, fire weather, severe wind storms, and tropical cyclones

While the overall issue of detecting changes in extreme weather events and their attribution remains ambiguous, most of the activity in this area relates to the attribution of single-particular extreme weather events. The most prominent effort is the World Weather Attribution (WWA; [worldweatherattribution.org](http://worldweatherattribution.org)), which is an international research initiative that focuses on for extreme event attribution that purports to analyze how climate change influences the likelihood and intensity of extreme weather events. Their approach used by the WWA is to use large ensembles of regional climate models to compare the event in today's climate, with a counterfactual – a pre-industrial counterfactual climate without human-caused warming influences.

WWA plays a prominent role in linking extreme weather to climate change, with its press releases attracting considerable attention in public and policy discussions. However, the WWA's tendency to extensive promotion of promote non-peer-reviewed findings, its funding ties, its open admission that they to shaping shape their analyses to serve purpose of litigation, and other its methodological challenges have sparked controversies, with critics questioning the robustness and impartiality of its conclusions (Pielke Jr. 2024). Despite these issues, WWA's work continues to shape influence climate science and media narratives. Technical criticisms of the approach include a neglect lack of a formal detection process; an implicit assumption that 100% of the post-industrial warming is caused by CO<sub>2</sub> greenhouse gases; and a failure to adequately account for natural internal climate variability.

Because EEA is relatively new many basic methodological issues have yet to be settled in the expert literature. An important challenge is the lack of data. Extreme events are by definition rare. Many analyses of extreme event types (including the US National Assessment Reports) only evaluate data since 1950 or 1970. –However, as emphasized by Chapter 7, many of the worst extreme weather and climate events in U.S. history occurred prior to the first half of the 20<sup>th</sup> century including in the early 19<sup>th</sup> century. And if paleoclimate reconstructions are considered, it becomes very difficult for an event to pass the detection thresholds of exceeding what is expected from natural variability, particularly if a reasonably sized geographic region is considered.

Another challenge is defining the event under study. There is a longstanding literature in statistics and econometrics on the challenge of analyzing data with outliers. The issue arises because a data series establishes a probability distribution defining the expected range of observations. If an outlier is observed it might indicate that the underlying process giving rise to the data distribution



has changed (which in the weather context would mean ~~that a climate~~ change has been detected) or that the underlying process has multiple regimes each with a different probability distribution, in which case observing an outlier simply means we were temporarily in a different regime, but the system itself was unchanged. If a time series contains only a single outlier event at the end of the series it is not possible to determine which model is the correct one (Chen and Liu 1993). For instance, there might be an “ordinary” weather regime that yields a distribution of summer daytime highs in a particular coastal region, and a second “heatwave” regime that kicks in when an inland blocking event occurs, which yields a temperature distribution centered 15°C higher than the first one. A day with temperatures 13°C above normal would either be an extreme heat anomaly under the first regime or a somewhat cool event under the second, and we have no way in this case of knowing on statistical grounds which view is correct.

Visser and Petersen (2012) and Sardeshmukh et al. (2015) both point out that different distributions may fit observed data equally well but yield very different implications about the likelihood of a specific weather event. Visser and Petersen argue that, in view of the deep uncertainties of extreme weather analysis drawing a connection between individual events and global climate change should be avoided. ~~Furthermore,~~ the existence of an outlier at the end of a data series poses the problem that estimates of the event probabilities will be biased whether the outlier is included or excluded (Barlow et al. 2020). Methods to eliminate the bias have not yet been established, leading some experts (e.g. Miralles and Davison 2023) to argue that in settings in which a data series contains a single extreme event at the end, estimation of a return period for the extreme event will be so biased and uncertain it should be avoided altogether.

In spite of these concerns, the U.S. is presently considering something like the WWA, which is being investigated by a NASEM Panel on Attribution of Extreme Weather and Climate Events and their impacts (NASEM, 2025).

~~We provide a~~ case study ~~from of~~ a recent high impact extreme events in the U.S. ~~is provided to~~ illustrate the challenges and ambiguities in attributing the frequency and intensity of extreme weather events to human-caused warming.

#### ***98.46.1 Case study – 2021 Western North America heat wave***

The 2021 Western North America heat wave was an extreme ~~heat-wave~~ event that affected much of Western North America in late June 2021. In particular, surface temperature records were set in Portland, OR (116°F; previous record 107°F) and Seattle, WA (108 °F; previous record 103°F) (Mass et al., 2024).

The WWA team ~~generated~~ ~~generated~~ international headlines ~~for with~~ their analysis, ~~which~~ and provided the following attribution statements (WWA, 2021; Philip et al., 2022):

- Based on observations and modeling, the occurrence of this heatwave was virtually impossible without human-caused climate change.
- The event is estimated to be about a 1 in 1000-year event in today’s climate.
- The event would have been at least 150 times rarer without human-induced climate change.

- This heatwave was about 2°C hotter than it would have been if it had occurred at the beginning of the industrial revolution (when global mean temperatures were 1.2°C cooler than today).

But an important  ~~caveat—counter~~ to the first claim is that other researchers concluded  ~~from—based~~ on historical weather data, that while a heat wave of the magnitude observed was indeed virtually impossible without anthropogenic climate change, it was also virtually impossible *with* climate change. Berco-Hickey (2022) noted “these temperatures were virtually impossible under any previously experienced meteorological conditions, with or without global warming.” McKinnon and Simpson (2022) stated “the most likely explanation remains that the weather event itself was ‘bad luck.’” The 2023 Oregon Climate Assessment (Fleischman 2023) concluded that the heat dome would have formed even without climate change and “There is no evidence that the highly unusual combination of weather features that drove the heat dome were made more likely by climate change, and climate models do not project an increase in the frequency of high-pressure ridges over the Pacific Northwest” (Fleischman 2023 p. 49).

Mass et al (2024) summarizes the proximate sequence of compound events leading to the heat wave. There was a record-breaking mid-tropospheric ridge over the Pacific Northwest, forced by a tropical disturbance in the western Pacific. This produced record-breaking mid-tropospheric temperatures, strong subsidence in the lower atmosphere, low-level easterly flow that produced downslope warming on regional terrain and the removal of cooler marine air, and an approaching low-level trough that enhanced downslope flow. The event occurred at a time of maximum solar insolation, and drier-than-normal soil moisture. Using a storyline approach, Mass et al. assessed that there is no trend in drought and dry soils in the Pacific Northwest; there is no evidence of global warming producing stronger ridges of high pressure, and no observed trend in heat waves or record temperatures in the region. They concluded that although anthropogenic warming may have contributed as much as 2°F to the magnitude of the event, there is little evidence of further amplification of the event from increasing greenhouse gases.

~~Berco-Hickey et al. (2022) conducted a statistical analysis of a model-based attribution study of this heat wave was conducted by Berco-Hickey et al. (2022). Because the event is a far outlier and far above the bounds of Generalized Extreme Value distributions fitted from historical data, they concluded that estimates of return times, quantitative changes in event magnitude and frequency, and probability of the extreme temperatures such as provided by the WWA are not accurate and should be interpreted as having low confidence. They found that hindcast attribution methods using an ensemble of regional climate models, combined with Pearl (2009) causal inferences, can provide limited and conditional information about the magnitude of the human influence on this heatwave – they provided a more highly constrained estimate that human activities caused a ~1.4°C–1.8°F increase in the daily maximum temperatures.~~

Zeder et al. (2023) also concluded that the methods employed by Philip et al. (2022, the WWA analysis) tend to overstate the rarity of extreme heat waves, leading to a biased perception of the effect of climate change on the heatwave event: “The tendency to overestimate the return period of observed extreme heatwave events may fuel the impression that seemingly impossible heatwave extremes are currently clustering at an unprecedented rate.”

The 2021 Western North America heatwave was a rare and unprecedented compound weather event, that broke century-old temperature records by as much as 9°F. While the WWA team received worldwide publicity for their rapid attribution claims blaming anthropogenic climate change, subsequent peer-reviewed analyses, which garnered far less media attention, showed that the event was caused by rare meteorological rare event conditions that was were not made more probable by global warming.

Commented [SK2]: Check if this is true

### 9.5 Summary

There is an ongoing scientific debate around attribution methods, particularly in attributing extreme weather events to climate change. The IPCC has long cautioned that methods to establish causality in climate science are inherently uncertain and ultimately depend on expert judgement.

There are two areas of substantive criticism of the IPCC assessment of the causes of the recent warming: inadequate assessment of natural climate variability, and inappropriate statistical methods.

Detection of extreme weather events is challenged by their rarity, requiring a long data set and a choice of region and spatial scale to evaluate their occurrence against the background of natural weather and climate variability.

The most robust attribution statements for an extreme event relate to an incremental change (e.g. a temperature change in degrees or percent change in rainfall). Statements related to return times, quantitative changes in event magnitude and frequency, and probability of the extremes are not accurate owing to an inadequate amount of data, and data are made with low confidence. There is no evidence in a change of weather or climate regime patterns from increasing greenhouse gases that would amplify or dampen extreme weather events, beyond basic thermodynamic considerations.

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The Social Cost of Carbon (SCC) is a tool for understanding the economic impact of carbon emissions, helping policymakers weigh the costs and benefits of climate policies. It estimates the damage caused by emitting one additional ton of CO<sub>2</sub>, expressed in dollars. The SCC is typically calculated using integrated assessment models (IAMs), which combine economic, climate, and social data. The process includes:

- Projecting future CO<sub>2</sub> emissions based on population growth, economic development, and technology (REFER TO SECTION XXX)
- Modeling climate responses to predict temperature increases and sea-level rise (REFER TO SECTIONS XXX)
- Assessing economic damages as property value losses due to rising sea levels, positive and negative impacts on agriculture, changes in heating and cooling expenditures, climate-related diseases such as malaria and dengue fever, and ecosystem losses.
- Discounting to present value, whereby future damages are converted to today's dollars using discount rates typically ranging from 1.5% to 3.0%

Even if science could provide a perfect forecast of global temperatures, each element of the economic impact analysis for climate change is the subject of radical uncertainties and serious debate.<sup>71</sup>

The models do not adequately account for potential adaptation or technical change that might alter the emissions pathway and resulting damages. In this respect, it is difficult to determine whether the incomplete treatment of adaptation and technological change in these IAMs under or overstate the likely damages (US Government 2010, p. 30).

Current models may underestimate damages by not fully incorporating non-market impacts (e.g., biodiversity loss) or catastrophic risks like climate tipping points, as highlighted in Rennert et al. (2022) *Nature* - Comprehensive evidence implies a higher social cost of CO<sub>2</sub>. The private benefit of carbon – the value of energy services provided by the use of fossil fuels – is ignored in the determination of the SCC. The private benefit of carbon has been estimated to be much higher than the social cost of carbon

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It is difficult to avoid the conclusion that the IAMs are simply too weakly justified and too varied to provide confidence in their estimates. However, the models do confirm the crucial role of three factors in determining the social cost of carbon: the magnitude of climate sensitivity (Section xxx), the size of the social discount rate, and the handling of possible catastrophic outcomes.

A high discount rate implies that people put less weight on the future and therefore that less investment is needed now to guard against future costs.<sup>77</sup> The use of a low discount rate supports the view that we should act now to protect future generations from climate

change impacts, given more importance to future generations' well-being in cost-benefit analyses. The choice of discount rate is contentious, affecting how much future damages matter today, and reflects ethical judgments about future generations.

Economist Robert Pindyck concludes that possible catastrophic outcomes are the dominant factor in determining the social cost of carbon.<sup>75</sup> However, catastrophic outcomes in the 21<sup>st</sup> century are off the table, now that extreme emissions scenarios are no longer judged to be plausible (REF TO PREVIOUS SECTIONS).

SCC estimates are highly uncertain due to unknowns in future economic growth, socioeconomic pathways, discount rates, climate damages, and system responses.

Despite pervasive uncertainties, in 2009 the US Interagency Working Group on Social Cost of Carbon was convened to provide a uniform estimate of the social cost of carbon using Integrated Assessment Models. This exercise engendered substantial criticism from legal scholars and economists. Criticisms included weakly defended assumptions about future economic growth and technological change, arbitrarily damage functions that were essentially guesses, and a very large range of plausible parameter values that can be used to obtain almost any result.<sup>73,74</sup>

It is increasingly being argued that the SCC is too variable to be useful for policymakers. Cambridge Econometrics stated in 2021 it's "time to kill it" due to uncertainties Cambridge Econometrics - Time to Kill Social Cost of Carbon. The UK and EU no longer use SCC for policy appraisal, opting for "target-consistent" carbon pricing, as noted in UK Government - Carbon Valuation and EU Carbon Pricing.

71 Daniel A. Farber, "Coping with Uncertainty: Cost-Benefit Analysis, the Precautionary Principle, and Climate Change," Washington Law Review 90, no. 4 (2015), <https://doi.org/dx.doi.org/10.2139/ssrn.2637105>.

72 Ibid.

73 Eric Posner and Johnathan Masur, "Climate Regulation and the Limits of Cost-Benefit Analysis," University of Chicago Public Law & Legal Theory Working Paper, no. 315 (2010).

74 Robert S Pindyck, "Climate Change Policy: What Do the Models Tell Us?," Journal of Economic Literature 51, no. 3 (September 2013): 860–872, <https://doi.org/10.1257/jel.51.3.860>.

75 Ibid.

76 "What Are Social Discount Rates?," Grantham Research Institute on climate change and the environment (The London School of Economics and Political Science, May 1, 2018), <https://www.lse.ac.uk/granthaminstitute/explainers/what-are-social-discount-rates/>.

77 Laurie T. Johnson and Chris Hope, "The Social Cost of Carbon in U.S. Regulatory Impact Analyses: An Introduction and Critique," Journal of Environmental Studies and Sciences 2, no. 3 (September 12, 2012): 205–221, <https://doi.org/10.1007/s13412-012-0087-7>.

78 Cass R. Sunstein, "The Catastrophic Harm Precautionary Principle."

79 Ibid.



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## Introduction

This document ~~originated had its origin in an initiative undertaken in late March 2025 when by Secretary Wright to assemble assembled an independent team~~asked the authors to write a brief report ~~for him~~ on issues in climate science relevant for energy policymaking, with particular focus on the question of whether carbon dioxide emissions ~~pose a danger to endanger~~ the US public. ~~The team~~ We authors of this report agreed on the usefulness of such a document and agreed to undertake the work on the condition that there ~~was to would~~ be no editorial oversight by the Secretary, the Department of Energy, or any other government personnel. This condition has been honored throughout the process and the writing team has worked with full independence.

The team began working in early April with a final submission deadline of May 28. Because of ~~t~~the short timeline and the technical nature of the material ~~meant we have not tried to produce that we could not comprehensively review of all topics. While the report is intended to be accessible for non-experts, we deliberately have omitted some introductory or explanatory material that can easily be accessed elsewhere. Nor have we attempted to survey entire literatures related to the topics selected for focus covered. The scientific and technical material herein is just a sample of the only samples vast literature on climate change but is, we believe, more than sufficient to establish our conclusions.~~

Commented [SK1]: In the references cited?

The team writing this report was not involved in, nor briefed on, any ~~Administration plans or administrative processes~~ related to a potential challenge to the 2009 EPA CO<sub>2</sub> Endangerment Finding. During the writing of this report we received no information about the Administration's plan on that matter. We were asked, however, to include some information related to the role of US motor vehicles in global climate change, since that is an issue of relevance to the Department of Energy.

The writing team wishes to ~~express its~~ grateful to ~~thanks to~~ Secretary Wright for the opportunity to prepare this report and for his support for independent scientific inquiry.

In addition to the uncertain sensitivity of the climate system to increasing CO<sub>2</sub>, future climate projections also depend upon uncertain estimates of how much “extra” CO<sub>2</sub> will accumulate in the atmosphere in the future. These uncertain estimates are a function of two components: (1) future rates of global anthropogenic CO<sub>2</sub> emissions, and (2) how fast the land and ocean remove extra CO<sub>2</sub> from the atmosphere.

#### Global carbon cycle and local emissions policy

Global carbon cycle models are used to quantify the second component, using estimates of various land and ocean processes that remove CO<sub>2</sub> from, and emit CO<sub>2</sub> into, the atmosphere. Our understanding of these processes was reviewed by Crisp et al. (2021). The natural fluxes of CO<sub>2</sub> in and out of the Earth’s surface are very large, many times anthropogenic emissions, but those CO<sub>2</sub> sources and sinks were assumed to be in approximate balance in pre-Industrial times, as evidenced by relatively constant levels of atmospheric CO<sub>2</sub> in centuries past derived from air bubbles in ice cores. This is one of the reasons why increasing atmospheric CO<sub>2</sub> levels are believed to be dominated by anthropogenic sources.

Specifically, fossil fuel burning (and to a lesser extent land use [biomass burning] and cement production) has led to steadily increasing CO<sub>2</sub> levels in the atmosphere, as shown in Fig.1.4.3.1.

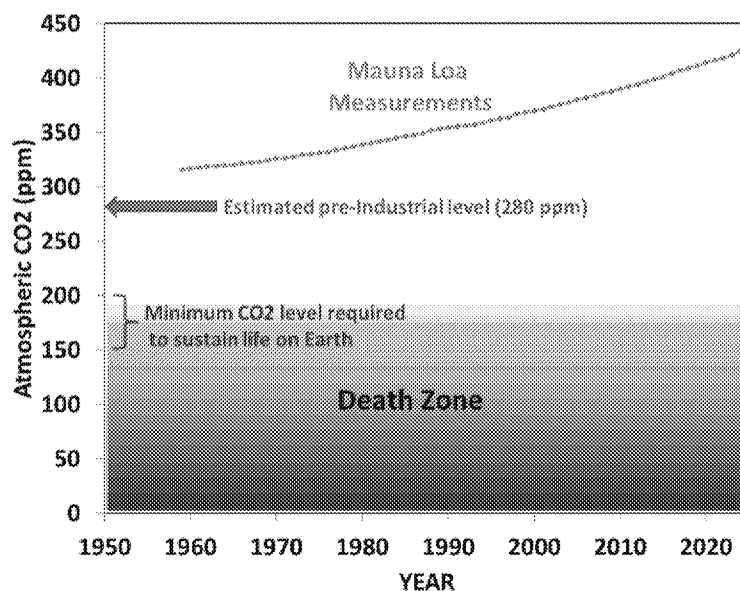


Fig. 1.4.3.1. Yearly average atmospheric CO<sub>2</sub> concentrations (1959-2024) measured at Mauna Loa, HI (green) compared to the estimated pre-Industrial CO<sub>2</sub> concentration of 280 ppm, and the estimated minimum levels required to sustain life on Earth (150 to 200 ppm). **NEED SOURCE**

As noted in Fig. X1, life on Earth requires CO<sub>2</sub> levels of at least 150 to 200 ppm. This is because the food chains on land and in the ocean begin with vegetation and biota that depend upon photosynthesis, which requires CO<sub>2</sub>.

CO<sub>2</sub> emissions from fossil fuel burning is a small component of the natural carbon cycle. About 44,000 Gigatonnes of carbon-equivalent (GtC) are stored in the atmosphere and oceans, mostly in the form of CO<sub>2</sub>. (Ciais et al. 2013). Between 150 and 200 GtC are released naturally each year through oceanic outgassing and land-based processes like plant decay and animal respiration. A variable but roughly equivalent amount is absorbed each year by the land and oceans, with a small net loss from the atmosphere because the formation of deep ocean sediment sequesters some carbon permanently. Global fossil fuel consumption and cement manufacture released about 10.3 GtC in 2023, up from 6.2 GtC in 1990 (Ritchie et al. 2024). Of this, about half is naturally sequestered through plant growth and oceanic uptake while the remainder, about half, adds to the atmospheric stock (Ciais et al. 2013).

The policy issues related to CO<sub>2</sub> are fundamentally different from those related to criterion air contaminants like SO<sub>2</sub> and NO<sub>x</sub> for two reasons. First, in the case of criterion air contaminants we are concerned with the local ground-level concentration, since that is what affects human welfare. But local variations in CO<sub>2</sub> levels do not affect human health, the potential channel of influence is through variations in the global climate which operates through the global average atmospheric CO<sub>2</sub> concentration. (Another influence is the positive local effect on crop productivity which will be discussed in Section 3.2). Second, policy can only change the flow of emissions, not the stock, and with criterion air contaminants the two are closely connected because the stock is relatively small. When emissions are reduced the local pollution concentration drops rapidly, usually on a time scale of a few days. Not so with the global average CO<sub>2</sub> concentration since global carbon cycle is vast and slow. A change in local emissions today will only have a very small global effect, and only after a long time lag. After a pulse (release) of CO<sub>2</sub> emissions to the atmosphere only about 40 percent (± 15%) of the emitted molecules will have been sequestered after twenty years. After a thousand years about 75 percent (± 10%) will have been sequestered, and the remainder will gradually be removed over the ensuing tens of thousands of years (Ciais et al. 2013, pp. 472-473). Consequently US CO<sub>2</sub> emission reductions will take decades or centuries to lead to a reduction in the global CO<sub>2</sub> concentration.

The CO<sub>2</sub> level as recorded at the Mauna Loa observatory in Hawaii is generally used as the representative global average concentration. The data are available online at [ [HYPERLINK "https://gml.noaa.gov/ccgg/trends/index.html"](https://gml.noaa.gov/ccgg/trends/index.html) ]. The concentration was about 316 ppm at the start of the record in 1959 and is now about 425 ppm, a 34 percent increase. The record exhibits monthly fluctuations of about 0.5—2.0 ppm due to plant growth and decay, superimposed on an upward trend that averages 1.7 ppm per year. To reduce the atmospheric stock of CO<sub>2</sub>, assuming the entire increase is anthropogenic, would require emissions to fall below the natural sequestration rate. The 1997 Kyoto Protocol proposed to cap industrial nations' CO<sub>2</sub> emissions at five percent below 1990 levels by the year 2012. Even though this policy ended up too costly for

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most nations to implement, full compliance would not have reduced atmospheric CO<sub>2</sub> levels. They would only have slowed down slightly slowly, reaching their projected 2100 level in 2105 instead (Wigley 1998). Similarly Lomborg (2016) used the well-known MAGICC climate model and showed that full compliance with the Paris Accord would delay hitting the baseline year 2100 levels about a decade later instead.

Thus, in contrast with conventional air pollution control, local actions yield extremely small local effects, and only after a long time lag. The practice of referring to unilateral US reductions as “combatting climate change” or “taking action on climate” reflects a profound misunderstanding of the scale of the issue.

#### Sequestration of CO<sub>2</sub>

As noted, each year natural processes remove a net amount of CO<sub>2</sub> equivalent to about 50% of global emissions. Thus, anthropogenic CO<sub>2</sub> emissions average twice what is required to explain the atmospheric rise in CO<sub>2</sub> concentration. The near-constancy of that 50% fraction also means that the more CO<sub>2</sub> humanity produces, the faster Nature removes it from the atmosphere. That 50% fraction changes somewhat from year to year due to natural carbon cycle imbalances from El Nino, La Nina, and varying weather patterns. There was also a substantial additional reduction in atmospheric CO<sub>2</sub> after the 1991 eruption of Mt. Pinatubo, a curious result that has yet to be explained (Angert et al., 2004).

The main processes which remove excess CO<sub>2</sub> from the atmosphere are increased production of land vegetation (especially at high latitudes), some increase in the sequestering of carbon in soils, and uptake of CO<sub>2</sub> by the ocean due to the increasing partial pressure of atmospheric CO<sub>2</sub> over that of CO<sub>2</sub> dissolved in the ocean. All twenty land carbon cycle models tracked by the Global Carbon Project (Friedlingstein et al., 2024) show land processes have been removing excess CO<sub>2</sub> at an increasing rate since 1959. This is consistent with a “global greening” phenomenon observed by satellites since monitoring of global greenness began in the 1982. This greening has been traced to CO<sub>2</sub> fertilization and greater drought tolerance of plants exposed to elevated CO<sub>2</sub> levels. While there had been some uncertainty whether a greening trend continued beyond 2000, the most recent research (Chen et al., 2023) has shown continued greening, with even some slight acceleration since 2000. Global greening is discussed further in Section 3.1.

While land vegetation has been responding positively to more atmospheric CO<sub>2</sub>, uptake of extra CO<sub>2</sub> by ocean biological processes remains too uncertain to be reliably measured. Our current understanding of these and many more carbon cycle processes was reviewed by Crisp et al. (2021).

When the two components required to estimate future atmospheric CO<sub>2</sub> concentrations are combined (anthropogenic emissions estimates along with carbon cycle model estimates of atmospheric CO<sub>2</sub> removal), we get estimates of future CO<sub>2</sub> concentrations required by climate models to estimate future rates of warming.

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IPCC Emission scenarios have long been biased upwards

For the IPCC 3<sup>rd</sup> and Fourth Assessment Reports a set of emission projections from the *Special Report on Emission Scenarios* were used, and hence were referred to as the SRES scenarios. McKittrick et al. (2012) showed that, when converted to per capita terms, the SRES scenario distribution was skewed upwards and incompatible with observed trends. McKittrick and Wood (2013) further showed that global energy market dynamics constrained global per capita CO<sub>2</sub> emissions to an extent not reflected in IPCC scenarios. The bias of the SRES scenarios was confirmed by analysis in Hausfather et al. (2019) who showed that observed atmospheric CO<sub>2</sub> levels tracked the lowest of the SRES forecast range.

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For the Fifth Assessment Report the IPCC developed a new set of scenarios called the Representative Concentration Pathways (RCP). Each RCP is identified by a number representing the increase in warming forcing in Watts per square meter over the 21<sup>st</sup> century resulting from GHG emissions. The RCP scenarios are thus called RCP2.6, RCP4.5, RCP6.0 and RCP8.5. RCP2.6 (implying a gain of 2.6 Watts per square meter) projects a GHG concentration pathway which implies warming remains well below 2°C. At the other end of the scale RCP8.5 is an extreme outcome implying nearly 5°C warming just in this century.

In both the academic literature and popular media RCP8.5 came to be referred to as the no-policy baseline, or “business-as-usual” scenario. It was used in this way to generate the reference outcome supposedly representing the 21<sup>st</sup> century world in the absence of emission reduction policies. But RCP8.5 was in fact an extreme high emissions scenario and its usage as a baseline has been grossly misleading. Hausfather and Peters (2020) writing in a commentary in *Nature* magazine, pointed out that RCP8.5 was developed as an extreme worst case scenario, and its misuse as a “business as usual” baseline has resulted in a large number of misleading studies and media reporting:

RCP8.5 was intended to explore an unlikely high-risk future. But it has been widely used by some experts, policymakers and the media as something else entirely: as a likely ‘business as usual’ outcome. A sizeable portion of the literature on climate impacts refers to RCP8.5 as business as usual, implying that it is probable in the absence of stringent climate mitigation. The media then often amplifies this message, sometimes without communicating the nuances. This results in further confusion regarding probable emissions outcomes, because many climate researchers are not familiar with the details of these scenarios in the energy-modelling literature.  
(Hausfather and Peters 2020)

The implausibility of the RCP8.5 scenario was examined by Burgess et al. (2021). They noted that RCP8.5 has already diverged from observed energy use trends, and the near future trends diverge sharply from those of the International Energy Agency (IEA) which provides market-based projections of energy use for coming decades. IEA trends are based on plausible extrapolations of current economic and demographic trends, and the results run below the entire envelope of RCP projections, implying not only that RCP8.5 is dubious, but even lower emission scenarios are looking unlikely. Burgess et al. comment (p. 8):

Beyond 2040, if the trends anticipated by energy agency forecasts continue, carbon intensity will continue diverging from AR5 and SSP baselines—especially from higher-emission scenarios such as RCP8.5, due to the assumptions about fossil-fuel expansion in these scenarios that are increasingly implausible.

The problem of bias towards alarmism in the climate impacts literature fueled by implausible extreme high emission scenarios was confirmed in a literature analysis by Pielke Jr. and Ritchie (2020). They found (p. 32) that between 2010 and 2020 some 16,800 scientific papers had been published using the RCP8.5 scenario, and (p. 16) that about 4,500 of the articles linked RCP8.5 with the concept of “business-as-usual”. They provided analyses of how RCP8.5 was misused not only by individual researchers, but by influential science agencies like the IPCC and the US National Climate Assessment (USNCA), which has directly led to misleading coverage in prominent media outlets. They provide the following example (p. 30):

The USNCA employed RCP8.5 as a baseline scenario, despite warning against such use, and compared it to RCP4.5 throughout its report to generate quantitative economic estimates of the benefits of mitigation. In a front page story, the *New York Times* promoted the report’s misuse of RCP8.5 as a baseline scenario:

“A major scientific report issued by 13 federal agencies on Friday presents the starkest warnings to date of the consequences of climate change for the United States, predicting that if significant steps are not taken to rein in global warming, the damage will knock as much as 10 percent off the size of the American economy by century’s end.”

Pielke and Ritchie (2020) reported new studies using RCP8.5 were appearing in the literature at a rate of about 20 per day, with about two per day specifically linking RCP8.5 and “business as usual.” They conclude (p. 34) that the climate research community has spent a decade “committing scientific resources to science fiction” (emphasis added):

“Derived estimates from RCP8.5 as “business as usual” such as future climate impacts, the impacts avoided from mitigation and the cost effectiveness and benefits of mitigation have no real-world meaning... **The scientific literature has become imbalanced in an apocalyptic direction.**”  
(Pielke Jr. and Ritchie p. 34)

The IPCC later modified the RCP scenarios to the “Shared Socioeconomic Pathway” or SSP scenarios, but these have continued the pattern of bias shown with the RCP and SRES scenarios. Figure 1.4.3.2, generated using the Resources for the Future Global Energy Outlook tool (RFF 2025). The black line shows total global observed CO<sub>2</sub> emissions from the International Energy Agency (IEA). The solid green line is the emission trajectory developed by BP energy taking account of current emission control policies and global energy use outlooks, current policy proposals. It overlaps a solid black line which represents the emission projection from the IEA also taking account of energy use projections and current policies. The dashed lines show the range of IPCC SSP policies.

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**Carbon dioxide emissions (Million metric tons), by Outlooks & Scenarios. Filtered by Region: World; Fuel: All; Outlook: 2023 Shell (Sky 2050).**

Source: RFF Global Energy Outlook at [www.rff.org/geo](http://www.rff.org/geo)

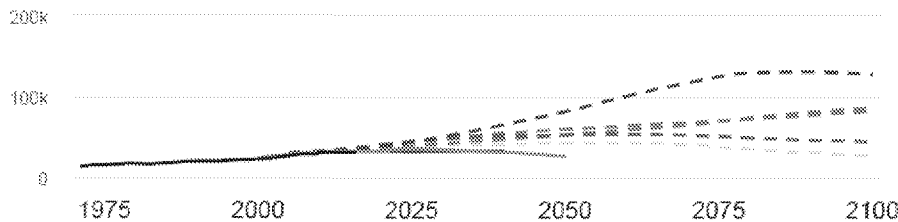


Figure 1.4.3.2. Observed and projected  $\text{CO}_2$  emissions. Source: RFF (2025).

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As of 2023 global  $\text{CO}_2$  emissions have been tracking *well below* the SSP scenarios especially the two highest ones (SSP5-8.5 and SSP3-7.0). As mentioned, most of the climate model projections relied upon for energy policy decisions have been from these two emissions scenarios or their RCP analogues, which exaggerated and unrealistic (e.g. Ritchie and Dowlatabadi, 2017; Pielke & Ritchie, 2017; Pielke & Ritchie, 2021).

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Summarizing:

- Unlike criterion air contaminants, local emissions and local levels of  $\text{CO}_2$  have no human health implications. The only potential effects are  $\text{CO}_2$  fertilization of plants (a benefit) and modifications of the global climate.
- The global carbon cycle heavily dampens the effect of changes in local  $\text{CO}_2$  emissions. Even global-scale emission reductions will have only small effects, long in the future.
- For decades the IPCC has used emission scenario envelopes that are grossly exaggerated against observed trends.
- The vast majority of academic climate “impacts” studies in recent years are based on scenarios like RCP8.5 that are implausible to the point of misleading. Usage of the RCP8.5 scenario amplifies the putative dangers of future baseline emissions and exaggerates the associated benefits of emission reduction policies.
- Despite ample evidence that scenario envelopes are exaggerated, and despite heavy criticism of this practice in the peer-reviewed literature, the IPCC’s most recent scenario set called SSP carries on with this deceptive pattern.

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## 5 Measuring Climate Sensitivity to CO<sub>2</sub> Forcing

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### 5.1 Introduction5.1 Model-based methods of computing climate sensitivity to GHGs

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The magnitude of the sensitivity of Earth's climate to increasing concentrations of CO<sub>2</sub> is at the heart of the scientific debate on anthropogenic climate change, and also the public debate on the appropriate policy response to increasing CO<sub>2</sub> in the atmosphere. Equilibrium Climate Sensitivity (ECS) refers to is defined as the expected amount of warming averaged over the Earth's surface in response to a doubling of CO<sub>2</sub>, after all climate systems have had time to adjust. Some systems, like temperatures in the troposphere, adjust very rapidly. Others may take decades or even centuries, such as the deep ocean and the cryosphere. A related metric which is sometimes more helpful for analysis on shorter time scales is the Transient Climate Response (TCR) defined as the amount of warming after 70 years in which atmospheric CO<sub>2</sub> goes up by one percent annually.

In 1979 the Charney (1979) Report for the US National Academy of Sciences proposed that the most likely value for ECS was 3.0°C plus or minus 1.5°C. With only minor variations this range was adopted and reaffirmed by the IPCC until the most recent AR6. The ECS range between 1.5 and 4.5°C is characterized by the IPCC AR5 as the *likely* range (66 percent probability); the AR5 stated that ECS is *extremely unlikely* (95 percent probability) to be below 1.0°C and very unlikely (90 percent probability) to exceed 6.5°C. This range of ECS values has remained stubbornly wide, despite many individual studies claiming to narrow it. Most recently, the IPCC AR6 narrowed its assessment of the *likely* range of ECS to 2.5–4.0°C and the *very likely* range to be between 2.0 and 5.0°C. This narrowing of the range on the low end is disputed, as will be discussed below.

Although ECS is of intrinsic scientific interest it is also of central importance to evaluating the public danger posed by GHG emissions. Uncertainties about ECS are highly consequential for policy making. As will be discussed in Section Chapter 13, economic models take the ECS value from climate science and use it to project the costs of CO<sub>2</sub> emissions. The traditional ECS value (3.0 °C) has typically yielded modest global social costs of CO<sub>2</sub> emissions, enough to justify some policy actions though mostly deferred to later in the century. If ECS is very high (4.5°C or above) aggressive immediate emission controls become more imperative, whereas values closer to 2.0°C have been shown to be compatible with social costs of emissions being zero or even negative over the coming decades imply that no CO<sub>2</sub> emission controls are economically justifiable (Dayaratna et al. 2016, 2020). Obtaining a precise ECS estimate is therefore important for policy guidance. Obtaining a precise estimate is impossible, so policy making needs to account for the uncertainty.

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In large-scale General Circulation Models (GCMs, aka climate models) ECS is not imposed as a direct parameter, instead it emerges from the behaviour of the underlying components of the model. These, however, are under the control of the modeler, so ultimately a model's ECS can be said to be built into it. Direct warming from CO<sub>2</sub> doubling is only about 1°C (Hall and Manabe 1997); the rest, to the extent more happens, arises due to climate feedbacks which are inherently more difficult to predict and model.

In 1979 the Charney (1979) Report for the US National Academy of Sciences proposed that the most likely value for ECS was 3.0°C plus or minus 1.5°C. Hence the best estimate was a likely tripling of the CO<sub>2</sub> effect through feedbacks. With only minor variations this range was adopted and reaffirmed by the IPCC until the most recent AR6.

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### 5.12 Model-based methods of computing climate sensitivity to GHGs

The ECS range has been obtained primarily by examining the behaviour of climate models, but since key components of models are under the control of modelers this is not dispositive of the actual climate's sensitivity.

There are approximately three dozen computer climate models operated by research groups around the world (Cannon 2024). GCMs are valuable tools for understanding the climate system from a theoretical perspective. But the models have become so complex, often with 1 million or more lines of computer code (Brown-Steiner 2024), that it would be prohibitively expensive and time consuming for anyone to replicate the models' projections of climate change, let alone test the myriad model approximations embedded in the computer codes; a climate model typically takes hundreds of experts many years to develop (McSweeney and Hausfather 2018). As a result, these models are published in the scientific literature with little to no independent evaluation (Pirtle et al 2010). Climate modeling thus stands as an unusual class of scientific endeavor wherein researchers validating the scientific claims of others — a hallmark of science (National Academy of Science 2019) — becomes impractical, if not impossible.

In large-scale General Circulation Models (GCMs, aka climate models) ECS is not imposed as a direct parameter, instead it emerges from the behaviour of the underlying components of the model. Collections of parameterizations are often chosen to produce an expected value of climate sensitivity, particularly with regards to sub-grid-scale cloud processes. Otherwise plausible models and parameter selections have been discarded because of perceived conflict with this warming rate, or a version to a model's climate sensitivity being outside an accepted range. For example, Mauritsen and Roeckner (2020) state the following regarding their Max Planck Institute climate model:

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"We have documented how we tuned the MPI-ESM1.2 global climate model to match the instrumental record of warming: an endeavor which has clearly been successful. Due to the historical order of events, the choice was to do this practically by targeting an ECS of about 3 K using cloud feedbacks, [emphasis added] as opposed to tuning the aerosol forcing."

In other words, the modelers chose an ECS value of 3°C and then tuned the cloud parameterizations to match their intended result.

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Direct warming from CO<sub>2</sub> doubling is only about 1°C (Hall and Manabe 1997); ~~the rest to the extent more happens, arises due higher values further warming arises to~~ from climate feedbacks that are not explicitly resolved by the model but rely on parameterizations of physical processes ~~which are inherently more difficult to predict and model~~. Higher values of ECS arise primarily from positive cloud feedbacks. The magnitude, and even the sign, of cloud feedbacks is the greatest source of uncertainty. Elements of cloud feedback include changes in the latitudinal distribution of clouds, changes in the distribution of cloud height (changes in low versus high clouds), changes to the phase of clouds (ice versus liquid), changes in cloud particle size (associated with changes in concentration and/or composition of aerosol particles), changes in the precipitation efficiency of clouds, and even changes in how clouds are distributed over the daily solar cycle [source 35]. It is difficult for climate models to simulate any of these cloud processes correctly owing to their small scale, let alone predict how they will change in the future. Further, cloud processes modulate the magnitudes of the water vapor, lapse rate, and the surface albedo feedbacks [source 36].

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ECS can be determined from climate model simulations by doubling the concentration of CO<sub>2</sub>, allowing several centuries for the warming to equilibrate. To avoid the necessity of long simulations, "effective climate sensitivity" is commonly evaluated from a 150-year simulation in response to a

sudden quadrupling of CO<sub>2</sub>. The spread of ECS values from the CMIP5 climate models (used in the AR5) was 2.0–4.7°C; the spread has increased for the CMIP6 models (used in the AR6) to between 1.8 and 5.7°C [sources 37,38]. Far from the science being settled in relation to the response of the climate system to increasing greenhouse gas concentrations, insofar as it is represented by climate models, uncertainties appear to be growing. The main cause of the overall upward shift in ECS in CMIP6 relative to CMIP5 is a larger positive cloud feedback, driven by changes to the cloud parameterizations in many CMIP6 models [source 39]

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~~THIS ISN'T VERY RELEVANT.~~ There are approximately three dozen computer climate models operated by research groups around the world (Cannon 2024). GCMs are valuable tools for understanding the climate system from a theoretical perspective. But the models have become so complex, often with 1 million or more lines of computer code (Brown-Steiner 2024), that it would be prohibitively expensive and time-consuming for anyone to replicate the models' projections of climate change, let alone test the myriad model approximations embedded in the computer code: a climate model typically takes hundreds of experts many years to develop (McSweeney and Hausfather 2010). As a result, these models are published in the scientific literature with little to no independent evaluation (Pirille et al. 2010). Climate modeling thus stands as an unusual class of scientific endeavor wherein researchers validating the scientific claims of others—a hallmark of science (National Academy of Science 2019)—becomes impractical, if not impossible.

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While the models are often touted as being accurate representations of the "basic physics" governing the climate system, they still have problems with model "drift," in which the models slowly change temperature over centuries for no apparent reason (Grandey et al. 2023). The tendency to drift is adjusted for by climate modelers imposing the arbitrary assumption that Earth's climate system does not produce long-term climate change, unless caused by humans (Sen-Gupta et al. 2013). By suppressing all slow-moving warming and cooling in this way this biases model-based research away from potential natural causes of climate change since it implies there can be no warming trends except in response to external forcing. In addition recent research suggests many models do not even conserve energy (Irving 2021)—a violation of the First Law of Thermodynamics. The First Law holds that energy can be neither created nor destroyed; to the extent that climate models fail to conserve energy, it can spontaneously appear (or disappear) for no apparent reason, causing a fictitious temperature change. This is a particularly important consideration since global warming theory is first and foremost based upon tiny changes in the global energy balance assuming the First Law holds.

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Because of concerns about model tuning and the high sensitivity to cloud parameterizations, the IPCC AR6 (2021) did not rely on climate model simulations in their assessment of climate sensitivity, relying on other methods in its assessment instead, chiefly a recent empirical estimate.

For all these reasons it should come as no surprise that the various models' responses to a hypothetical doubling of atmospheric CO<sub>2</sub> above pre-industrial levels produces a very wide range of ECS values in current models, from 1.83°C to 5.64°C in the IPCC AR6. This wide range of responses—the largest in over 30 years of the global climate modeling enterprise—demonstrates large remaining uncertainties in climate modeling and thus in the projection of global climate impacts imputed to human activities. It also implies that ECS cannot be determined from climate models alone since the range is too wide to be informative. For that reason scientists have increasingly turned to empirical methods.

#### 4.5.2.3 Empirical Data-driven methods of computing climate sensitivity to GHGs

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Climate sensitivity can also be estimated from instrumental records of surface temperatures and ocean heat content, combined with estimates of how climate forcings (e.g., greenhouse gases, solar, volcanoes, aerosols) have changed in the past. [source 40] Using this information, a simple empirical model called an Energy Balance Model can be estimated. It requires estimating a feedback parameter which appears in the denominator of the resulting equation for ECS. NO EQUATIONS whose uncertainties are highly amplified in the resulting ECS (Roe and Baker, 2007). A small amount of uncertainty about the number in the denominator of a fraction can lead to very large uncertainties in the magnitude of the fraction itself. Roe and Baker (2007) pointed out that for this reason uncertainties in climate feedbacks are "highly amplified" in the resulting ECS.

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The accuracy of the data-driven methods depends on the quality of the input data. Assumptions are needed about ocean heat storage, and the ocean data is inadequate. The greatest source of uncertainty is the amount and composition of aerosol particles and their interactions with cloud radiative properties (the so-called aerosol indirect effect). Climate models exhibit warming in response to GHGs but cooling in response to aerosols (Schwartz et al. 2007). Observed 20<sup>th</sup> century warming can be shown to be consistent either with low ECS and low aerosol cooling or high ECS and high aerosol cooling. Since fossil fuel use adds both GHGs and aerosols to the atmosphere, both effects need to be estimated to isolate the warming effect of CO<sub>2</sub>. Over time, the IPCC's estimate of the cooling effect of aerosols has declined (Lewis 2022).

Paleoclimate proxies are also used to evaluate the sensitivity of past climates, by comparing paleoclimate changes in the Earth's temperatures to estimates of changes in forcings. The two most informative periods are the last glacial maximum (around 20,000 years ago), which was about 3–7°C colder than today, and a mid-Pliocene period (roughly three million years ago), which was 1–3°C warmer than today. [source 41] The limits on cooling during the last glacial maximum give the best single evidence that high values of climate sensitivity are unlikely. However, paleoclimate estimates are associated with very large uncertainties in the estimated temperatures and forcings. Further, estimates of climate sensitivity based on past climate states may not be representative of the current state of the climate system.

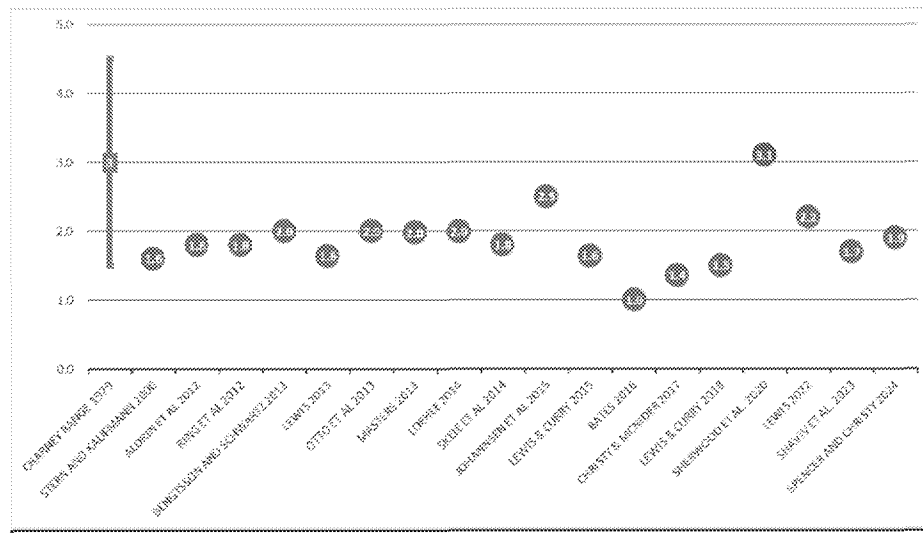
A significant amount of effort since the EF has gone into estimating ECS empirically. There are several challenges to this work.

- First, it requires good data but observations of some key climatic systems, especially the oceans, are available in only very limited amounts.
- Second, identifying the effect of CO<sub>2</sub> requires simultaneously identifying the effect of aerosols. Climate models exhibit warming in response to GHGs but cooling in response to aerosols (Schwartz et al. 2007). Observed 20<sup>th</sup> century warming can be shown to be consistent either with low ECS and low aerosol cooling or high ECS and high aerosol cooling. Since fossil fuel use adds both GHGs and aerosols to the atmosphere, both effects need to be estimated to isolate the warming effect of CO<sub>2</sub>. Over time the IPCC's estimate of the cooling effect of aerosols has declined (Lewis 2022).
- Third, the simple empirical model typically used for the estimation, called an Energy Balance Model, requires estimating a feedback parameter which appears in the denominator of the equation for ECS. A small amount of uncertainty about the number in the denominator of a fraction can lead to very large uncertainties in the magnitude of the fraction itself. Roe and Baker (2007) pointed out that uncertainties in climate feedbacks are "highly amplified" in the resulting ECS.

Since 2012 many studies have appeared in the literature tackling these various uncertainties. A recurring theme in the climate literature is that ECS estimates based on historical data turn out to be smaller than ECS estimates inferred from climate models (Sherwood and Forest 2024). About 15 estimates appeared in the peer-reviewed literature between 2012 and 2024 yielding ECS best estimates between 1.0°C and 2.5°C, although critics have questioned some of the methods and the data quality. For the AR6 the IPCC placed primary weight on the results of Sherwood et al. (2020) that combined historical and paleoclimate proxies and yielded a best estimate of 3.1°C. Lewis (2022) raised a number of concerns about this result. An early empirical estimate (Stern and Kaufmann 2000) was 1.6°C, though this predated development of the Energy Balance Model method. Figure 4.25.1 shows the point or best estimates from 17 subsequent studies all appearing in the peer-reviewed literature after the TSD since 2012. The Charney range is shown for contrast. The average ECS point estimate in the post-2012 sample is 1.8°C. The highest estimate, from Sherwood et al. (2020), is shown in red: it is the one that was used highlighted by the IPCC for the AR6 and used to guide their assessment of the ECS range (Forster et al. 2021). The one adjacent to it, Lewis (2022), was published subsequent to the AR6 and presented an extensive critique of Sherwood et al. (2020).

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shows the result of, among other things, using the same statistical method (Bayesian inference) but applying more updated aerosol forcing data in the AR6 as well as some other recent updates to the source data. These updates dropped the ECS best estimate to 2.2°C closer to the usual empirical range. The IPCC, following Sherwood et al. (2020) had estimated only a 5 percent probability that ECS was below 2.3°C, whereas Lewis (2022) estimated it was over 50 percent.



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Figure 4.25.1: Empirical best estimates of ECS. Vertical axis: °C.

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I don't think this is needed. Lewis (2022) is not a historical empirical method, but rather uses the same approach as Sherwood et al. and AR6 in combining historical, paleo and feedback

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~~approaches. I don't think that the older ones are useful because the data is pretty old, and methods outdated. Lewis (2022) is clearly within the the AR5 range, I don't think we need to resurrect the old stuff.~~

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~~Key concerns raised by Lewis include, including methodological errors, outdated input values, and use of subjective versus objective Bayesian priors in the analysis. Lewis' analysis found that climate sensitivity is estimated to be much lower and better constrained than in the Sherwood et al. analysis – median 2.462°C (1.758–2.7°C in the 17–83 percent *likely* range), and 1.556–3.2°C in the 5–95 percent *very likely* range). Lewis' analysis implies that climate sensitivity is considerably more likely to be below 2°C than above 2.5°C. The IPCC AR6 estimated only a 5 percent probability that ECS was below 2.3°C, whereas Lewis (2022) estimated it to be over 50 percent. The most recent publications on the debate between Sherwood et al. and Lewis further defend their respective positions: Sherwood and Foster (2024) and Lewis (2025).~~

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~~A recent hypothesis argument, which the IPCC AR6 emphasized, is that empirical data-driven ECS estimates might understate the future warming response to GHGs due to based on a so-called "pattern effect" (Forster et al 2021). The tropical Pacific is believed to be highly influential on the overall efficiency with which the Earth's climate radiates heat to space, but heat in some parts regions heat is more efficiently removed from the climate system than from others. If in a warming climate there is a weakening of the west-to-east temperature gradient in the tropical Pacific the result would be a concentration of warming in a region where heat is less efficiently removed, raising the ECS of the Earth's climate system. Most climate models simulate that rising GHGs will weaken the east-west temperature gradient, which led the IPCC in the AR6 to conclude that empirical data-driven ECS estimates understated what would be the future observed ECS value.~~

~~However, Seager et al. (2019) pointed out that, contrary to models, the east-west temperature gradient has been strengthening rather than weakening over time. They further argued that the mechanism predicting otherwise in climate models was based on a faulty characterization of oceanic dynamics and there is no reason to expect the gradient to weaken. A similar argument was recently made by Lee et al. (2024), who concluded that "the trajectory of the observed trend reflects the response to increasing GHG loading in the atmosphere", in other words GHG warming should lead to a future strengthening rather than a weakening of the temperature gradient. Increased efficiency of atmospheric cooling implies, if anything, that the future ECS in a warming climate may be lower than at present current estimates.~~

### 5.5 Transient Climate Response

~~The Transient Climate Response (TCR) is of greater utility in providing an observational constraint on climate sensitivity. TCR is the amount of warming that would occur at the time when CO<sub>2</sub> doubles, having increased gradually by 1 percent each year over a period of 70 years. Relative to the ECS, observationally-determined values of TCR avoid the problems of uncertainties in ocean heat uptake and the fuzzy boundary in defining equilibrium arising from a range of timescales for the longer-term feedback processes (e.g., ice sheets). TCR is more generally related to peak warming and better constrained by historical warming than ECS. The IPCC AR6 judged the *very likely* range of TCR to be 1.2–2.4°C. [source 47] In contrast to ECS, the upper bound of the TCR is more tightly constrained. For comparison, the TCR values determined by Lewis (2023) is 1.25 to 2.0°C, showing much better agreement with the AR6 values than was seen in a comparison of the ECS values.~~

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~~A related but more flexible parameter is the Transient Response to cumulative carbon Emissions, or TCRE, which relates global temperature change to the cumulative emissions. TCRE is based upon a linear relationship between global average temperature and cumulative emissions, which holds for~~

cumulative emissions of up to 2 teratons of carbon. For a given value of TCRE, we can calculate the estimated amount of warming expected over a future period in response to scenarios of cumulative carbon emission. The IPCC AR6 provides a *very likely* range for TCRE of 1.0–2.3°C, with a median value of 1.6°C.<sup>48</sup>

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As will be discussed in Section Chapter 6.5 a real-world ECS below the model average is supported by studies which show climate models on average estimate too much warming at the surface and in the troposphere compared to observations over the past 50 years. Also it aligns with evidence from consistent fingerprinting (Section 6.7) that model responses to GHGs need to be scaled down quite a bit to align with observed trends.

### 5.6 Summary

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In the past 5 years, there is a growing realization that climate models are not fit for the purpose of determining the sensitivity of the climate to increasing CO<sub>2</sub> (ECS), owing to the dependence of this sensitivity on poorly resolved processes related to clouds and water vapor.

Data-driven approaches using historical data and paleoclimate reconstructions are now regarded as more reliable for determining ECS, but their reliability is diminished by data inadequacies. The IPCC AR6 upper bound for the *likely* range of ECS is 4.0°C, lower than the AR5 value of 4.5°C. This lowering of the upper bound seems well justified by the paleoclimatic estimates of the ECS. The IPCC AR6 lower bound for the *likely* range of ECS is 2.5°C, substantially higher than the AR5 value of 1.5°C. This raising of the lower bound of the likely range of ECS has received a substantial challenge from the analysis of Lewis (2022, 2025) that finds the lower bound of the likely range to be 1.75°C with a median value of 2.16°C. Other lines of evidence supporting a lower bound on the ECS range below the IPCC AR6 value are discussed in Chapters 6 and 7.

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Estimates of the transient climate response (TCR; TCRE) are more tightly constrained on the upper bound than the ECS.

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Mauritsen, T., & Roeckner, E. (2020). Tuning the MPI-ESM1.2 global climate model to improve the match with instrumental record warming by lowering its climate sensitivity. *Journal of Advances in Modeling Earth Systems* 12, e2019MS002037. [HYPERLINK "https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2019MS002037"]

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Zelinka, M. D., Myers, T. A., McCoy, D. T., Po-Chedley, S., Caldwell, P. M., Ceppi, P., et al. (2020). Causes of higher climate sensitivity in CMIP6 models. *Geophysical Research Letters*, 47, e2019GL085782. [HYPERLINK "https://doi.org/10.1029/2019GL085782"]

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In summary:

- ECS cannot be determined from climate modeling alone since models are too complex and uncertain to narrow the range

- Climate models on average embed process assumptions that yield a projected warming of about 3.0°C from CO<sub>2</sub>. Empirical estimates since the TSD however imply the climate is much less sensitive to CO<sub>2</sub> than this.
- A large number of empirical ECS estimates have been centered at or below 2°C. This aligns with other independent forms of empirical evidence pointing towards low ECS.



## 5 Climate Sensitivity to CO<sub>2</sub> Forcing

### 5.1 Introduction

The magnitude of the sensitivity of Earth's climate to increasing concentrations of CO<sub>2</sub> is at the heart of the scientific debate on anthropogenic climate change, and also the public debate on the appropriate policy response to increasing CO<sub>2</sub> in the atmosphere. Equilibrium Climate Sensitivity (ECS) refers to the expected amount of warming averaged over the Earth's surface in response to a doubling of CO<sub>2</sub>, after all climate systems have had time to adjust. Some systems, like temperatures in the troposphere, adjust very rapidly, whereas others such as the deep ocean and ice sheets may take decades or even centuries. A related metric which is helpful for analysis on shorter time scales is the Transient Climate Response (TCR), defined as the amount of warming after 70 years in which atmospheric CO<sub>2</sub> increases by one percent annually.

In 1979 the Charney (1979) Report for the US National Academy of Sciences proposed that the most likely value for ECS was 3.0°C plus or minus 1.5°C. The ECS range between 1.5 and 4.5°C is characterized by the IPCC AR5 as the *likely* range (66 percent probability); the AR5 stated that ECS is *extremely unlikely* (95 percent probability) to be below 1.0°C and very unlikely (90 percent probability) to exceed 6.5°C. This range of ECS values has remained stubbornly wide, despite many individual studies claiming to narrow it. Most recently, the IPCC AR6 narrowed its assessment of the *likely* range of ECS to 2.5–4.0°C and the *very likely* range to be between 2.0 and 5.0°C. This narrowing of the range on the low end is disputed, as will be discussed below.

Uncertainties about ECS are highly consequential for policy making. As will be discussed in Chapter 13, economic models take the ECS value from climate science and use it to project the costs of CO<sub>2</sub> emissions. The traditional ECS value (3.0 °C) has typically yielded modest global social costs of CO<sub>2</sub> emissions, enough to justify some policy actions though mostly deferred to later in the century. If ECS is very high (4.5°C or above) aggressive immediate emission controls become more imperative, whereas values closer to 2.0°C have been shown to imply that no CO<sub>2</sub> emission controls are economically justifiable (Dayaratna et al. 2016, 2020). Obtaining a precise estimate is impossible, so policy making needs to account for the uncertainty.

### 5.2 Model-based methods of computing climate sensitivity to GHGs

The ECS ranges for the IPCC AR4 and AR5 ~~has been~~<sup>were</sup> obtained primarily by examining the behaviour of climate models. ~~For the AR6 the IPCC changed course and turned to a more direct data-driven methodology. Here we discuss some of the pitfalls of using climate models to try to determine the Earth's climate sensitivity. However, key components of climate models include adjustable parameters and parameterization of small-scale processes such as clouds, hence the models are not~~ <sup>dispositive of the actual climate's sensitivity. There are approximately three dozen computer climate models operated by research groups around the world (Cannon 2024). GCMs are valuable tools for understanding the climate system from a theoretical perspective. But the models have become so complex, often with 1 million or more lines of computer code (Brown-Steiner 2024), that it would be prohibitively expensive and time-consuming for anyone to replicate the models' projections of climate change, let alone test the myriad model approximations embedded in the computer codes; a climate model typically takes hundreds of experts many years to develop (McSweeney and Haugfather 2019). As a result, these models are published in the scientific literature with little to no independent evaluation (Pirde et al 2010). Climate modeling thus stands as an unusual class of scientific endeavor where in researchers validating the scientific claims of others—a hallmark of science (National Academy of Science 2019)——becomes impractical, if not impossible. LACK OF</sup>

FORMAL VERIFICATION AND VALIDATION IS NOT THE BIGGEST PROBLEM. I DON'T THINK THIS CHAPTER IS THE PLACE TO GO THROUGH ALL THE PHILOSOPHICAL ISSUES WITH CLIMATE MODELS. I WROTE A WHOLE CHAPTER ON THIS IN MY BOOK

THE AR6 decided that climate models are useless for determining ECS, and we can just agree with them

Climate sensitivity ECS represents an emergent property of climate models—that is, it is not directly parameterized or tuned. However, collections of parameterizations are often chosen to produce an expected value of climate sensitivity, particularly with regards to sub-grid-scale cloud processes. Collections of parameterizations are often chosen to produce an expected value of climate sensitivity, particularly with regards to sub-grid-scale cloud processes. Otherwise plausible models and parameter selections have been discarded because of perceived conflict with this warming rate, or aversion to a model's climate sensitivity being outside an accepted range. For example, Mauritsen and Roeckner (2020) state the following regarding their Max Planck Institute climate model *(emphasis added)*:

"We have documented how we tuned the MPI-ESM1.2 global climate model to match the instrumental record of warming; an endeavor which has clearly been successful. Due to the historical order of events, the choice was to do this practically by *targeting an ECS of about 3 K using cloud feedbacks*, *(emphasis added)* as opposed to tuning the aerosol forcing."

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In other words, the modelers chose an ECS value of 3°C and then tuned the cloud parameterizations to match their intended result.

Direct warming from CO<sub>2</sub> doubling is only about 1°C (Hall and Manabe 1997); further warming arises from climate feedbacks that are not explicitly resolved by the model but rely on parameterizations of physical processes. Higher values of ECS arise primarily from positive cloud feedbacks *whose magnitude, and even the sign, of cloud feedbacks is the greatest source of uncertainty are very uncertain*. Elements of cloud feedback include changes in the latitudinal distribution of clouds, changes in the distribution of cloud height (changes in low versus high clouds), changes to the phase of clouds (ice versus liquid), changes in cloud particle size (associated with changes in concentration and/or composition of aerosol particles), changes in the precipitation efficiency of clouds, and even changes in how clouds are distributed over the daily solar cycle (Curry and Webster, 1999). It is difficult for climate models to simulate any of these cloud processes correctly owing to their small scale, let alone predict how they will change in the future. Further, cloud processes modulate the magnitudes of the water vapor, lapse rate, and the surface albedo feedbacks.

ECS can be determined from climate model simulations by doubling the concentration of CO<sub>2</sub> *and* allowing several centuries for the warming to equilibrate. To avoid the necessity of long simulations, "effective climate sensitivity" is commonly evaluated from a 150-year simulation in response to a sudden quadrupling of CO<sub>2</sub>. The spread of ECS values from the CMIP5 climate models (used in the AR5) was 2.0–4.7°C; the spread has increased for the CMIP6 models (used in the AR6) to between 1.8 and 5.7°C (Chen et al, 2021). Far from the science being settled in relation to the response of the climate system to increasing greenhouse gas concentrations, insofar as it is represented by climate models, uncertainties appear to be growing. The main cause of the overall upward shift in ECS in CMIP6 relative to CMIP5 is a larger positive cloud feedback, driven by changes to the cloud parameterizations in many CMIP6 models (Zelinka et al., 2020)

Because of concerns about model tuning and the high sensitivity to cloud parameterizations, the IPCC AR6 (2021) did not rely on climate model simulations in their assessment of climate sensitivity, relying instead on other methods in its assessment instead, chiefly a recent empirical estimate.

### 5.3 Data-driven methods of computing climate sensitivity to GHGs

Climate sensitivity can also be estimated from instrumental records of surface temperatures and ocean heat content, combined with estimates of how climate forcings (e.g., greenhouse gases, solar, volcanoes, aerosols) have changed in the past (Otto et al., 2013). Using this information, a simple empirical model called an Energy Balance Model can be estimated. It requires estimating a feedback parameter whose uncertainties are highly amplified in the resulting ECS (Roe and Baker, 2007).

The accuracy of the data-driven methods depends on the quality of the input data. Assumptions are needed about ocean heat storage, and the ocean data is inadequate. The greatest source of uncertainty is the amount and composition of aerosol particles and their interactions with cloud radiative properties (the so-called aerosol indirect effect). Climate models exhibit warming in response to GHGs but cooling in response to aerosols (Schwartz et al. 2007). Observed 20<sup>th</sup> century warming can be shown to be consistent either with low ECS and low aerosol cooling, or high ECS and high aerosol cooling. Since fossil fuel use adds both GHGs and aerosols to the atmosphere, both effects need to be estimated to isolate the warming effect of CO<sub>2</sub>. Over time, the IPCC's estimate of the cooling effect of aerosols has declined (Lewis 2022).

Paleoclimate proxies are also used to evaluate the sensitivity of past climates, by comparing paleoclimate changes in the Earth's temperatures to estimates of changes in forcings. The two most informative periods are the last glacial maximum (around 20,000 years ago), which was about 3–7°C colder than today, and a mid-Pliocene period (roughly three million years ago), which was 1–3°C warmer than today. [source 41] The limits on cooling during the last glacial maximum give the best single evidence that high values of climate sensitivity are unlikely. However, paleoclimate estimates are associated with very large uncertainties in the estimated temperatures and forcings. Further, estimates of climate sensitivity based on past climate states may not be representative of the current state of the climate system.

A recurring theme in the climate literature is that ECS estimates based on historical data are smaller than ECS estimates inferred from climate models (Sherwood and Forest 2024). About 15 estimates based on historical data appeared in the peer-reviewed literature between 2012 and 2024 yielding ECS best estimates between 1.0°C and 2.5°C, although critics have questioned some of the methods and the data quality. For the AR6, the IPCC placed primary weight on the results of Sherwood et al. (2020) that combined historical and paleoclimate proxies and yielded a best estimate of 3.1°C. Lewis (2022) raised a number of concerns about this result, including methodological errors, outdated input values, and use of subjective versus objective Bayesian priors in the analysis. Lewis' analysis found that climate sensitivity is estimated to be much lower and better constrained than in the Sherwood et al. analysis – median 2.2°C (1.8–2.7°C in the 17–83 percent *likely* range, and 1.6–3.2°C in the 5–95 percent *very likely* range). ~~Lewis' analysis implies that climate sensitivity is considerably more likely to be below 2°C than above 2.5°C.~~ The IPCC AR6 estimated only a 5 percent probability that ECS was below 2.3°C, whereas Lewis estimated it to be over 50 percent. The most recent publications on the debate between Sherwood et al. and Lewis further defend their respective positions: Sherwood and Foster (2024) and Lewis (2025).

An interesting footnote is that in 1983, the US National Research Council conducted a follow-up study to the 1979 Charney Report and referring to the estimated sensitivity range of 1.5°C to 4.5°C said:

"The climate record of the past hundred years and our estimates of CO<sub>2</sub> changes over that period suggest that values in the lower half of this range are more probable."  
Nierenberg et al. (1983 p. 2)

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Lewis' analysis likewise implies that climate sensitivity is likely in the lower half of the original 1979 Charney range.

A recent argument, which the IPCC AR6 emphasized, is that data-driven ECS estimates might understate the future warming response to GHGs based on a so-called "pattern effect" (Forster et al 2021). The tropical Pacific is believed to be highly influential on the overall efficiency with which the Earth's climate radiates heat to space, but in some regions heat is more efficiently removed from the climate system than from others. If in a warming climate there is a weakening of the west-to-east temperature gradient in the tropical Pacific, the result would be a concentration of warming in a region where heat is less efficiently removed, raising the ECS of the Earth's climate system. Most climate models simulate that rising GHGs will weaken the east-west temperature gradient, which led the IPCC in the AR6 to conclude that data-driven ECS estimates understated the *future* ECS value.

However, Seager et al. (2019) pointed out that, contrary to models, the east-west temperature gradient has been strengthening rather than weakening over time. They further argued that the mechanism predicting otherwise in climate models was based on a faulty characterization of oceanic dynamics and there is no reason to expect the gradient to weaken. A similar argument was recently made by Lee et al. (2024), who concluded that "the trajectory of the observed trend reflects the response to increasing GHG loading in the atmosphere"; in other words, GHG warming should lead to a future strengthening rather than a weakening of the temperature gradient. Increased efficiency of atmospheric cooling implies, if anything, that the future ECS in a warming climate may be *lower* than current estimates.

### 5.5 Transient Climate Response

The Transient Climate Response (TCR) is of greater utility in providing an observational constraint on climate sensitivity. TCR is the amount of warming that would occur at the time when CO<sub>2</sub> doubles, having increased gradually by 1 percent each year over a period of 70 years. Relative to the ECS, observationally-determined values of TCR avoid the problems of uncertainties in ocean heat uptake and the fuzzy boundary in defining equilibrium arising from a range of timescales for the longer-term feedback processes (e.g., ice sheets). TCR is more generally related to peak warming and better constrained by historical warming than ECS. The IPCC AR6 judged the *very likely* range of TCR to be 1.2–2.4°C. [source 47] In contrast to ECS, the upper bound of the TCR is more tightly constrained. For comparison, the TCR values determined by Lewis (2023) is 1.25 to 2.0°C, showing much better agreement with the AR6 values than was seen in a comparison of the ECS values.

A related but more flexible parameter is the Transient Response to cumulative carbon Emissions, or TCRE, which relates global temperature change to the cumulative emissions. TCRE is based upon a linear relationship between global average temperature and cumulative emissions, which holds for cumulative emissions of up to 2 teratons of carbon. For a given value of TCRE, we can estimate the ~~estimated~~ amount of warming expected over a future period in response to scenarios of cumulative carbon emission. The IPCC AR6 provides a *very likely* range for TCRE of 1.0–2.3°C, with a median value of 1.6°C.<sup>48</sup>

As will be discussed in Chapter 6, a real-world ECS below the model average is supported by studies which show climate models on average estimate too much warming at the surface and in the troposphere compared to observations over the past 50 years. Also, lower values align with evidence from consistent fingerprinting (Section 7) that model responses to GHGs need to be scaled down quite a bit to align with observed trends.

## 5.6 Summary

In the past 5 years, there is a growing realization that climate models are not fit for the purpose of determining the sensitivity of the climate to increasing CO<sub>2</sub> (ECS), owing to the dependence of this sensitivity on poorly resolved processes related to clouds and water vapor.

Data-driven approaches using historical data and paleoclimate reconstructions are now regarded as more reliable for determining ECS, but their reliability is diminished by data inadequacies. The IPCC AR6 upper bound for the *likely* range of ECS is 4.0°C, lower than the AR5 value of 4.5°C. This lowering of the upper bound seems well justified by the paleoclimatic estimates of the ECS. The IPCC AR6 lower bound for the *likely* range of ECS is 2.5°C, substantially higher than the AR5 value of 1.5°C. This raising of the lower bound of the likely range of ECS has received a substantial challenge from the analysis of Lewis (2022, 2025) that finds the lower bound of the likely range to be 1.75°C with a median value of 2.24°C. Other lines of evidence supporting a lower bound on the ECS range below the IPCC AR6 value are discussed in Chapters 6 and 7.

~~Estimates of the transient climate response (TCR, TCR6) are more tightly constrained on the upper bound than the ECS.~~

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## 6 Challenges in Attributing Cause in Climate Change

### 6.1 Introduction

The detection and attribution process is concerned with assessing the causal relationship between one or more drivers and a responding system. The Intergovernmental Panel on Climate Change (IPCC) provides clear definitions for distinguishing between detection of climate change and attribution of cause. ~~detection and attribution in climate science, based on their Sixth Assessment Report (AR6). These terms are crucial for understanding climate change impacts and are used to assess whether observed changes are significant and what caused them. As defined by the IPCC AR6 WGI Glossary (IPCC, 2025):~~

*Detection:* "Detection of change is defined as the process of demonstrating that climate or a system affected by climate has changed in some defined statistical sense, without providing a reason for that change. An identified change is detected in observations if its likelihood of occurrence by chance due to internal variability alone is determined to be small, for example, <10%."

*Attribution:* "Attribution is defined as the process of evaluating the relative contributions of multiple causal factors to a change or event with a formal assessment of confidence."

~~The definition of detection emphasizes a Both steps rely on statistical approach analysis. Detection focusing focuses on whether changes are significant enough to stand out from natural variability random variation without yet attributing causes regardless of cause.~~

~~The attribution process Attribution involves comparison of observed events to model-generated counterfactuals. Since experimentation on the climate is not possible attribution requires statistical inference to assess involves assessing how much human activities, such as industrial GHG emissions, versus natural factors, like volcanic eruptions, contribute to explain observed changes, with a structured confidence level to reflect scientific certainty. Attribution methods requires the evaluation of the contributions of assume all external and internal drivers to of the system change are known and represented.~~

~~While the IPCC's definitions are clear, there is are ongoing scientific debates around attribution methods, particularly especially in for attributing extreme weather events to climate change. The IPCC has long cautioned that methods to establish causality in climate science are inherently uncertain and ultimately depend on expert judgement. The Fourth Assessment Report: The Physical Science Basis (Hegerl et al., 2007) explained it as follows:~~

'Attribution' of causes of climate change is the process of establishing the most likely causes for the detected change with some defined level of confidence... unequivocal attribution would require controlled experimentation with the climate system. Since that is not possible, in practice attribution of anthropogenic climate change is understood to mean demonstration that a detected change is 'consistent with the estimated responses to the given combination of anthropogenic and natural forcing' and 'not consistent with alternative, physically plausible explanations of recent climate change that exclude important elements of the given combination of forcings' (IPCC, 2001)... The



approaches used in detection and attribution research described above cannot fully account for all uncertainties, and thus ultimately expert judgement is required to give a calibrated assessment of whether a specific cause is responsible for a given climate change.

The Fifth Assessment Report Working Group II makes the following statement: (W Cramer et al., 2014):

“Two broad challenges to the detection and attribution of climate change impacts relate to observations and process understanding. On the observational side, high-quality, long-term data relating to natural and human systems and the multiple factors affecting them are rare. In addition, the detection and attribution of climate change impacts requires an understanding of the processes by which climate change, in conjunction with other factors, may affect the system in question.”

sets ▼

Because of the complexity of the causal chains in the climate system, investigation of these relationships is exceptionally challenging.

## 6.2 Attribution methods

The Intergovernmental Panel on Climate Change (IPCC) employs several attribution methods to assess the causes of observed climate changes, distinguishing between natural and human-induced factors. Below is a concise description of the key attribution methods that have been used by the IPCC:

Optimal Fingerprinting uses statistical linear regression techniques to compare explain variations in observed climate data with as a weighted sum of climate model simulations run with and without anthropogenic forcings of the responses to individual forcings (e.g., anthropogenic greenhouse gases, aerosols, natural forcings like solar variability). A regression model estimates the contribution of each forcing to observed changes, accounting for natural variability and model uncertainties. The data used in the regression model are weighted to try to minimize the influence of random noise and the estimation method is chosen to take account of climate model error.

Pattern Correlation Methods analyze spatial or temporal patterns of climate variables (e.g. temperature or precipitation) to identify similarities between observed changes and model-simulated responses to specific forcings. This method is useful for attributing shifts in atmospheric circulation or sea surface temperature patterns.

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Time Series Analysis examines temporal changes in climate variables to attribute trends to specific forcings. This approach compares long-term observed trends to model simulations with and without anthropogenic forcings. This method helps distinguish between short-term natural variability (e.g., El Nino) and long-term anthropogenic signals. It exploits statistical differences between anthropogenic forcing and natural variability to see which one dominates observed temperatures, and also uses variations in the timing of changes to determine if causal dependence across data series can be inferred.

Commented [RM1]: Other than Santer's TAR contributions and a paper by Wehner I have never seen the IPCC rely on this method. And the example Santer and Wehner cite, namely tropospheric amplification, doesn't match the data anyway as we show in Ch 6

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~~Multi-Step Attribution connects changes to impacts and then to forcings. An example is linking greenhouse gas emissions to warming, warming to increased heatwaves, and heatwaves to specific societal impacts.~~

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*Process-Based Attribution* focuses on understanding the physical mechanisms behind observed changes. This approach combines observations, climate models, and theoretical understanding to attribute changes in specific processes to forcings. This approach is often used for regional climate phenomena, such as monsoon changes or polar amplification.

~~Multi-Model and Ensemble Approaches use multiple climate models (e.g. CMIP6 ensemble) to account for uncertainties and improve confidence in attribution results. Large ensembles of simulations help separate the forced climate signal from internal variability.~~

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*Extreme Event Attribution* assesses the role of human influence in the likelihood of occurrence or intensity of extreme weather events (e.g. heat waves, droughts). Methods include:

- ~~Fraction of Attributable Risk quantifies how much anthropogenic climate change has altered the probability of an event.~~
- Probabilistic Event Attribution uses large ensembles of climate model simulations to compare event likelihood in a world with and without human influence observed events to model-generated counterfactuals.
- Storyline Approach examines the physical processes driving an event and evaluates how anthropogenic forcings may have modified those processes.

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### 6.3 Attribution of global warming

Attribution statements for global warming in the three most recent IPCC Assessment reports are:

AR4: "Most of the observed increase in global average temperatures since the mid-20<sup>th</sup> century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations." (IPCC, 2007)

AR5: "It is *extremely likely* that more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentrations and other anthropogenic forcings together. The best estimate of the human-induced contribution to warming is similar to the observed warming over this period." (IPCC, 2013)

AR6: "The *likely* range of total human-caused global surface temperature increase from 1850–1900 to 2010–2019 is 0.8°C to 1.3°C, with a best estimate of 1.07°C. It is *likely* that well-mixed GHGs contributed a warming of 1.0°C to 2.0°C, other human drivers (principally aerosols) contributed a cooling of 0.0°C to 0.8°C, natural drivers changed global surface temperature by –0.1°C to +0.1°C, and internal variability changed it by –0.2°C to +0.2°C. It is *very likely* that well-mixed GHGs were the main driver of tropospheric warming since 1979." (IPCC, 2021)

The AR4 and AR5 attribution statements reference the warming ~~to since~~ the mid-20<sup>th</sup> century, the period when greenhouse gas emissions began rapidly increasing. The words “most” and “more than half” are deliberately imprecise, potentially ranging from 51 to 99% of the warming – presumably this imprecision is to account for structural uncertainties such as natural internal variability. The confidence level increases from *very likely* to *extremely likely* from AR4 to AR5. The structure of the attribution statement in the AR6 is fundamentally different, referencing the warming to the period 1850-1900. The AR6 attribution statement is more precise numerically, but with a lower level of confidence at “likely” – the AR6 attributes essentially all of the warming to increases in greenhouse gases. The most confident statement from the AR6 relates to the tropospheric warming since 1979, using the words “main driver” and “*very likely*.”

There are ~~two-three~~ areas of substantive criticism of the IPCC assessment of the causes of the recent warming: inadequate assessment of natural climate variability, and inappropriate statistical methods, and substantial discrepancies between models and observations. The latter is discussed in Chapter 6, particularly section 6.4. The other two are discussed herein. Both of these issues are relevant not only in context of the main policy-relevant statement of the IPCC concerning attribution of the recent warming, but also because the global warming attribution provides the basis for extreme event attribution

### 6.3.1 Natural climate variability

The IPCC AR6 states that natural external drivers since 1850-1900 have changed global surface temperature by  $-0.1^{\circ}\text{C}$  to  $+0.1^{\circ}\text{C}$ , and internal variability has changed it by  $-0.2^{\circ}\text{C}$  to  $+0.2^{\circ}\text{C}$  – on average, having essentially no net impact on the warming since 1850-1900. This assessment of the contributions of natural variability has been disputed by a number of publications that question the magnitudes of the contributions from solar forcing and internal variability from the large-scale ocean circulations (R Connolly et al, 2021; W Soon, 2023).

If the Equilibrium Climate Sensitivity to  $\text{CO}_2$  is low (REF PREVIOUS CHAPTER), then natural climate variability becomes more important in the attribution of the recent warming. Further, if natural variability is higher, then estimates of the Equilibrium Climate Sensitivity from the historical period would be lower (Scafetta, 2023).

#### *Solar variability*

The IPCC AR5 concluded that the best estimate of radiative forcing due to Total Solar Irradiance (TSI) changes for the period 1750–2011 was  $0.05 \text{ W/m}^2$  (Myrhe et al., 2014). The IPCC AR6 acknowledges a much larger range of estimates of changes in TSI over the last several centuries, stating that the TSI between the Maunder Minimum (1645–1715) and the second half of the twentieth century increased by  $0.7\text{--}2.7 \text{ W/m}^2$ , a range that includes both low and high variability TSI data sets (Gulev, 2021). However, the recommended forcing dataset for the CMIP6 climate model simulations used in the AR6 for attribution studies averages two data sets with low solar variability (Matthes, 2017).

While the IPCC AR6 shows a substantially greater solar impact than does the AR5, the overall impact on the climate was assessed to be small compared to anthropogenic forcing of climate

change. However, the impact of solar variations on the climate is uncertain and subject to substantial debate - something that you would not infer from the IPCC assessment reports (Lockwood, 2012; Connolly et al., 2021).

Exactly how TSI has changed over time has been a challenging problem to resolve. Since 1978, there have been direct measurements of TSI from satellites. However, the data exhibit non-negligible inconsistencies, and interpreting any multi-decadal trends in TSI requires comparisons of observations from overlapping satellites. Substantial uncertainty exists in the TSI composites, particularly owing to a gap in coverage during 1989 to 1992 that prevented direct cross-calibrations between two successive satellites (N Scafetta, 2019). This rather arcane issue of cross-calibration of two satellite records has profound implications. There are a number of several rival composite TSI datasets, disagreeing as to whether TSI increased or decreased during the period 1986–96 (the ACRIM gap; see Chapter 4). Further, the satellite record of TSI is used for calibrating proxy models, whereby past solar variations are inferred from sunspots and cosmogenic isotope measurements (Velasco Herrera et al., 2015).

There is substantial evidence for high solar activity in the second half of the 20<sup>th</sup> century (starting in 1959) and extending into the 1990's, before a decline in the early 21<sup>st</sup> century; this period is often termed the “Modern Maximum.” (Chatzistergos et al, 2023; Solanki et al, 2004; Usoskin et al, 2007). However, some scientists have concluded that it is not possible to be confident of any multi-decadal trend in TSI (Schmutz, 2021).

As a result of this uncertainty, some reconstructions for past values of TSI (since 1750) have low variability, implying a very low impact of solar variations on global mean surface temperature, whereas datasets with high TSI variability can explain more than 70% percent of the temperature variability since preindustrial times (Scafetta, 2013; Stefani, 2021). Hence, the choice of which TSI satellite record used in an analysis can substantially influence how much climate change is attributed to human versus natural forcings.

~~A review article on this topic was recently published in the journal *Research in Astronomy and Astrophysics* (Connolly et al., 2023). The article had 23 co-authors with a range of perspectives, but who were united by their agreement not to take the consensus approach of the IPCC. Rather, the paper emphasized where dissenting scientific opinions exist as well as identifying areas where there is scientific agreement. The authors found that the Sun/climate debate is an issue where the IPCC's consensus statements were prematurely achieved through the suppression of dissenting scientific opinions. MOVE TO CH 4~~

There is growing evidence that other aspects of solar variability, which are referred to as solar indirect effects, amplify TSI forcing or are independent of TSI forcing. Scafetta et al. (2023) suggests that ~80% of solar influence on climate may stem from non-TSI mechanisms. Candidate processes include: solar ultraviolet changes; energetic particle precipitation; atmospheric-electric-field effect on cloud cover; cloud changes produced by solar-modulated galactic cosmic rays; large relative changes in the magnetic field; and the strength of the solar wind. Solar indirect effects are not included in climate models, although indirect methods of estimating these effects suggest significant influence. However, claims of non-TSI mechanisms influencing climate are uncertain

and debated.

#### *Natural variability of large-scale ocean circulations*

Variations in global mean surface temperature are linked to recurrent large-scale variations in ocean circulation patterns. These circulation patterns include the Atlantic Multidecadal Oscillation (AMO), the Pacific Decadal Oscillation (PDO) and the El Niño-Southern Oscillation (ENSO). These circulation patterns influence ocean heat uptake and heat distribution, and also influence atmospheric circulation patterns and cloud distributions. There is some debate as to whether these variations are strictly internal to the climate system, or whether this variability can have a solar/astrophysical origin or can be influenced by large volcanic eruptions.

While climate models simulate the large-scale ocean circulations and internal climate variability, the simulated magnitude in the multi-decadal band is too low in most models relative to observations, and the phasing of the variability in long-term climate simulations is not synced with the actual, observed climate variations (Kravtsov et al. 2024). Averaging multiple simulations from climate models effectively averages out the internal variations, leaving only the forced climate variability (e.g., CO<sub>2</sub> forcing). With most of the modern warming beginning in the late 1970's, the recent 50-year warming is on the same time scale as the multi-decadal oscillations of the AMO and PDO.

Here are summary statements from the IPCC AR5 and AR6 reports:

"Decadal variability in the Pacific, associated with the PDO or IPO, contributes significantly to regional and global temperature trends, but the relative contributions of internal variability and external forcing are difficult to disentangle in CMIP5 simulations." (IPCC, 2013)

"Since AR5, there has been increased understanding of the role of internal variability, such as ENSO, PDO, and AMO, in modulating regional climate trends. However, limitations in simulating the exact timing and amplitude of these modes in CMIP6 models contribute to uncertainties in attributing observed changes to anthropogenic forcing (high confidence)." (IPCC, 2021)

The amplitude of the peak-to-trough impact of the multi-decadal oscillations on global temperatures has been assessed by the IPCC AR6: "The likely range of change due to internal variability is -0.2°C to +0.2°C (IPCC, 2021)." This implies a trough-to-peak change of 0.4°C. Over many centuries, any global temperature changes from the troughs and peaks will cancel out, with little to no net impact.

However, with a nominal timescale of 60-80 years for oscillations such as the AMO and PDO, the timing of the peaks and troughs can be confused with the secular trend. This becomes very relevant for attributing the warming for the 50 years since 1975, during which most of the warming has occurred. Even if climate models have the correct amplitude of the multidecadal oscillations, the timing of the peaks and troughs is not adequately simulated, with each model and individual ensemble simulating a different phasing. Once the simulations of the ensemble members and

different models are averaged, the natural internal variability contribution is averaged out, effectively cancelling the role of natural internal variability in the attribution process.

The Great Pacific Climate Shift of 1976-1977 was a notable climatic event characterized by an abrupt change in the North Pacific Ocean's atmosphere-ocean system that interacted with global climate patterns. This shift is closely associated with the Pacific Decadal Oscillation (PDO) that oscillates between warm and cool phases over decades. The 1976 shift marked a transition from a predominantly negative (cool) PDO phase (1947-1976) to a positive (warm) phase (1977 through 2000), with significant implications for global and regional climate patterns including the frequencies of El Niño and La Niña events. The Great Pacific Climate Shift coincided with the beginning of a period of accelerated global warming (REF TO A FIG OF GLOBAL TEMP ANOMALIES ELSEWHERE IN DOC) When the Great Pacific Climate Shift is accounted for in climate attribution analyses since 1950, it has been found that 40 percent or more of the warming in the second half of the 20<sup>th</sup> century was caused by natural internal variability (McLean et al., 2009; Tung and Zhou, 2013; Chylik et al., 2016; Scafetta, 2021).

**6.3.2 ~~Statistical methods~~Optimal fingerprinting**

Optimal fingerprinting is a statistical technique introduced by Allen and Tett (1999) that compares observed climate data with to climate model simulations to identify patterns (or "fingerprints") associated with human or natural influence forcing. It involves taking a vector of observed climate changes, such as warming rates in locations around the world, and decomposing them into a weighted sum of "signals", which are analogues to the observations generated by climate models with different types of forcings. The weights are chosen using a regression method called Total Least Squares. The analysis commonly uses just two signals, one generated by models using only anthropogenic forcings and one using only natural forcings. Attempts to use three signals (for instance dividing the anthropogenic component into GHG and aerosol forcing) has tended to yield inconclusive results (Jones et al. 2016). If the estimated weighting coefficient attached to a signal is significantly different from zero that signal is said to be "detected". If it is close to 1.0 the model generating the signal is said to be consistent with observations. If it is less than 1.0 that implies the model signal for that forcing is too strong and needs to be scaled down, and vice-versa. Both the observed data and the signals are weighted using a model-generated estimate of patterns of randomness in the climate system so as, in principle, to put maximum weight on regions where natural variability is minimized.

Optimal fingerprinting has been heavily used is the primary tool for attribution in the climate literature for establishing attribution; studies Studies applying it have been cited thousands of times, and it has been prominently featured by the IPCC since the Third Assessment Report in 2001.

A series of papers by McKittrick (McKittrick 2022a, 2022b, 2023, 2025) has challenged the statistical methods commonly used in optimal fingerprinting and broader attribution analyses method, based on arguing that it is inherently unreliable and that commonly adopted used practices in econometrics can provide more valid results. Statistical theory requires that for regression models to yield unbiased coefficients a set of assumptions called the Gauss-Markov

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conditions must hold. These critiques highlight potential biases that could lead to over- or under-estimation of human influence on climate, and problems with the method that reduce confidence in the analysis results.

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McKittrick (2022a) challenged the methodology introduced by Allen and Tett (1999) for climate change attribution, which is a cornerstone of optimal fingerprinting. McKittrick argues that the Allen and Tett (1999) methodology violates key conditions of the Gauss-Markov theorem, particularly the requirement that the conditional expectation of errors must be zero. This violation leads, leading to potentially biased and inconsistent estimates of attribution fingerprinting coefficients, undermining the reliability of the method. Chen et al (2023) confirmed this analysis and argued that the method could yield unbiased results but only under stringent assumptions that are unlikely to hold in practice. McKittrick (2022b) and (2023) raised a further concern that climate scientists—virtually alone among scientific disciplines—have used an estimation method called Total Least Squares (TLS) to estimate anthropogenic greenhouse gas signal coefficients, despite its tendency to be unreliable unless some strong assumptions hold that in practice are unlikely to be true. Under conditions which easily arise in optimal fingerprinting for climate attribution, TLS yields estimates with large positive biases. Thus, any study that has used TLS for optimal fingerprinting without verifying that it is appropriate in the specific data context has likely overstated the result.

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McKittrick (2025) presented an empirical example comparing the results of conventional optimal fingerprinting against methods drawn from mainstream econometrics which are known to be valid for the specific application of signal detection. While the IPCC optimal fingerprinting method yields an anthropogenic signal coefficient close to 1.0 on a global temperature data set spanning 1900 to 2010, consistent estimation yields a coefficient around 0.4, which rises to about 0.65 on data spanning 1980 to 2010, implying the model response to greenhouse gases needs to be scaled down by about half to optimally match observations. The natural forcing signal coefficient by contrast is between 2.0 and 4.0, implying the climate model signals of natural forcing need to be scaled up two- to four-fold to match observed climate change. The fingerprinting coefficients estimated in McKittrick (2025), when used to scale the average sensitivity of the climate models used to generate the forcing signals in his data set, imply a Transient Climate Sensitivity of 1.4°C which matches the estimate by Lewis (2022) using a different estimation method and multiple independent data sets.

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While these analyses do not prove that all of the results from using these methods the IPCC optimal fingerprinting method are wrong, it does show that the basis on which they were believed to be correct is non-existent – hence reducing confidence in the results. McKittrick's work underscores the importance of statistical rigor in attributing climate changes and the need to bridge the gap between econometric and climatological approaches.

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### 6.3.3 Time series methods

Alternative approaches to assessing causality between GHGs and climate have emerged from the econometrics literature, specifically from methods used to infer directions of causality in finance and macroeconomic variables. One method uses a technique called “Granger causality”, named after the economist Clive Granger. If two variables X and Y tend to move closely together over time it can be difficult to tell which one drives the other. Granger causality refers to the

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supposition that if knowing the current value of X significantly improves our forecasts of Y, but not the other way around, we can conclude X influences (“Granger causes”) Y but not the reverse.

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An application of Granger causality to the well-known Vostok ice core data revealed an important error by Al Gore in his documentary *An Inconvenient Truth*. Gore drew attention to the coherence of temperature and CO<sub>2</sub> changes over a 440,000 year span and asserted that it implied CO<sub>2</sub> was the driver of temperature changes. Davidson et al. (2015) examined the series and found that temperature Granger causes CO<sub>2</sub> but not the other way around. In other words while CO<sub>2</sub> and temperature are closely correlated over time, warming (cooling) appears to drive increases (decreases) in CO<sub>2</sub> levels on long time scales but there is no evidence in the record that CO<sub>2</sub> changes drive subsequent warming or cooling.

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Another approach to determining causality between time series variables uses a concept called nonstationarity. It has a precise mathematical definition but for simplicity it can be thought of as the difference between a series that reverts to the same mean over time, thus having “short memory”, versus one in which past changes accumulate indefinitely implying the series has “long memory”. In economics the stock market is said to have long memory because what is known about the drivers of share value accumulates each day; traders do not forget each morning what they knew the day or before. Many economic variables are nonstationary in this sense. But climate variables are typically expected to be stationary or have short memory. Whatever causes today’s wind patterns is unlikely to be affected by the wind that blew on this day a year ago.

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Nonstationarity leaves mathematical patterns in time series called unit roots. Some authors have proposed that a fingerprint of anthropogenic climate change would be the presence of unit roots in global temperature data. The reasoning is that the climate system should normally be stationary, but if nonstationary economic activities like GHG emissions drive the climate, it will show up as unit roots in temperatures.

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It should be noted that finding unit roots in global temperatures can indicate a direction of causality between GHG forcing and climate, but it does not on its own measure whether the effect is large or small.

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There have been many published tests for the presence of unit roots in temperatures as well as tests for deeper patterns of nonstationarity in GHG and whether they match those in temperatures. Unfortunately tests for unit roots are very sensitive to minor variations in how the tests are constructed and conflicting results exist in the literature. Some authors report positive results which would support GHG causality (e.g. Dergiades et al. 2016) while others find either unit roots are not present, indicating lack of GHG causality (Balcombe et al. 2019, Razzak 2022) or are present but in a form inconsistent with GHG forcing (Beenstock et al. 2012).

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In summary, while a causal link from CO<sub>2</sub> to temperature is plausible due to the underlying physics, evidence based solely on statistical methods is unclear. Statistical analysis based on Granger causality indicates that over very long time scales CO<sub>2</sub> levels respond to temperature changes but do not drive them. On recent time scales it is not possible at this time to conclude an unambiguous unit root signal, which would correspond GHGs driving climate, exists in global

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temperature data.

McKittrick et al. (2023) addresses a paradox in climate attribution studies: standard trend models assume stationary (mean-reverting) error terms, while the climate econometrics literature suggests that if anthropogenic forcing is dominant, temperature trends should exhibit nonstationary (unit root) error terms, which could serve as a "fingerprint" for human influence. McKittrick and co-authors use tools from time series econometrics to resolve this issue, formalizing a hypothesis that temperature series contain both a nonstationary forcing component (due to anthropogenic influences) and a stationary "weather noise" component. This combination can bias unit root tests toward over-rejection, leading to misinterpretations in attribution studies.

McKittrick (2024) addresses the concern that for more than 20 years climate scientists virtually alone among scientific disciplines have used Total Least Squares (TLS) to estimate anthropogenic greenhouse gas signal coefficients, despite its tendency to be unreliable unless some strong assumptions hold that in practice are unlikely to be true. Little conditions which easily arise in optimal fingerprinting for climate attribution, TLS yields estimates with large positive biases. Thus, any study that has used TLS for optimal fingerprinting without verifying that it is appropriate in the specific data context has likely overstated the result.

While these analyses do not prove that all of the results from using these methods are wrong, it does show that the basis on which they were believed to be correct is non-existent, hence reducing confidence in the results. McKittrick's work underscores the importance of statistical rigor in attributing climate changes and the need to bridge the gap between econometric and climatological approaches.

#### 6.4 Extreme event attribution (EEA)

The IPCC AR6 provides an ambiguous assessment of the role of global warming in the historical record of extreme weather and climate events. Chapter 11 of WG1 states (Seneviratne et al., 2021):

"Evidence of observed changes in extremes and their attribution to human influence (including greenhouse gas and aerosol emissions and land-use changes) has strengthened since AR5, in particular for extreme precipitation, droughts, tropical cyclones and compound extremes (including dry/hot events and fire weather). Some recent hot extreme events would have been extremely unlikely to occur without human influence on the climate system."

By contrast, Chapter 12 of WG1 (Table 12.12) paints a different picture – presumably, the expert judgment of different groups of authors for the two chapters came to different conclusions (Ranasinghe, 2021):

- High confidence in an increase in extreme heat events in tropical regions where observations allow trend estimation and in most regions in the mid-latitudes, medium confidence elsewhere
- Medium confidence in a decrease in extreme cold events in Australia, Africa and most of northern South America where observations allow trend estimation
- No evidence of emergence in the historical period of a change in river floods, heavy precipitation, drought, fire weather, severe wind storms, and tropical cyclones

While the overall issue of detecting changes in extreme weather events and their attribution remains ambiguous, most of the activity in this area relates to the attribution of single extreme weather events. The most prominent effort is the World Weather Attribution (WWA; [worldweatherattribution.org](http://worldweatherattribution.org)), which is an international research initiative that focuses on extreme event attribution, analyzing how climate change influences the likelihood and intensity of extreme weather events. The approach used by the WWA runs large ensembles of regional climate models to compare the event in today's climate, versus a pre-industrial counterfactual climate without human-caused warming.

WWA plays a ~~significant~~ prominent role in linking extreme weather to climate change, using rapid probabilistic attribution to inform and its press releases attract considerable public and policy discussions.

However, the WWA's ~~tendency to promote non-peer-reviewed reports~~ findings, funding ties, open admission that they shape their analyses to serve purposes of litigation and other methodological challenges have sparked controversies, with critics questioning the robustness and impartiality of its conclusions (Pielke Jr. 2024). Also the WWA project is very new and is conducted by a rather small, tight-knit group (Weinkle 2025). Despite these issues, WWA's work continues to shape climate science and media narratives. Technical criticisms of the approach include: neglect of a formal detection process; an implicit assumption that 100% of the post-industrial warming is caused by CO<sub>2</sub>; and failure to adequately account for natural internal climate variability.

Because EEA is relatively new many basic methodological issues have yet to be settled in the expert literature. An important challenge is the lack of data. ~~Beyond the data raised by event attribution approaches, there exist major challenges to the detection step—a step that is commonly skipped, contra to the IPCC's established detection and attribution approach. Extreme events are by definition rare. Many analyses of extreme event types (including the US National Assessment Reports) only evaluate data since 1950 or 1970. However, as emphasized by Chapter xxx, many of the worst extreme weather and climate events in U.S. history occurred prior to the first half of the 20<sup>th</sup> century and including in the early 19<sup>th</sup> century. And if paleoclimate reconstructions are also considered, it becomes very difficult for an event to pass the detection thresholds of exceeding what is expected from natural variability, particularly if a reasonably sized geographic region is considered.~~

EEA is triggered by observing an extreme event, which causes selection bias (Miralles and Davison 2023). Out of all the weather systems that could be analyzed at any given time, the one selected is the one that experienced an extreme event, and the sample was stopped when the event took place. When the occurrence of an extreme event is the selection trigger and the stopping rule for the sample, any estimate of the return period of the extreme event will be biased (Barlow et al. 2020). If the extreme event itself is included in the data set the return period will be biased too low (we will conclude the events have become more probable in the future than they truly are) whereas if it is excluded the return period will be biased too high. The bias is smaller, however, when the extreme event is excluded (Barlow et al. 2020, Miralles and Davison 2023). Barlow et al. (2020)

attempt to obtain an unbiased return period estimator by using an adjustment to account for the probability of an extreme event being observed and the sample being stopped. But they point out that the trigger threshold cannot be set such that the only extreme event observed was the one that prompted the EEA at the end of the sample, otherwise the adjustment factor is undefined. But that requires the researcher to choose an arbitrary threshold for extreme events such that more than one can be said to have occurred over the available sample, and the bias adjustment can be sensitive to this step. Miralles and Davison argue that in settings in which an end-of-sample extreme event triggers the stop in sampling, estimation of a return period for the trigger event can yield such biased and uncertain results it should be avoided altogether.

Another challenge is defining the event under study. There is a longstanding literature in statistics and econometrics on the challenge of analyzing data with outliers. The issue arises because a data series establishes a probability distribution defining the expected range of observations. If an outlier is observed it might indicate that the underlying process giving rise to the data distribution has changed (which in the weather context would mean a climatic change has been detected) or that the underlying process has multiple regimes each with a different probability distribution, in which case observing an outlier simply means we were temporarily in a different regime, but the system itself was unchanged. If a time series contains only a single outlier event at the end of the series it is not possible to determine which model is the correct one (Chen and Liu 1993). For instance there might be an "ordinary" weather regime that yields a distribution of summer daytime highs in a particular coastal region, and a second "heatwave" regime that kicks in when an inland blocking event occurs, which yields a temperature distribution centered 15°C higher than the first one. A day with temperatures 13°C above normal would either be an extreme heat anomaly under the first regime or a somewhat cool event under the second, and we have no way in this case of knowing on statistical grounds which view is correct.

Visser and Petersen (2012) and Sardeshmukh et al. (2015) both point out that different distributions may fit observed data equally well but yield very different implications about the likelihood of a specific weather event. Visser and Petersen argue that, in view of the deep uncertainties of extreme weather analysis drawing a connection between individual events and global climate change should be avoided.

~~Beyond the issues raised by event attribution approaches, there exist major challenges to the detection step—a step that is commonly skipped, contra to the IPCC's established detection and attribution approach.~~

~~Extreme events are by definition rare. Many analyses of extreme event types (including the US National Assessment Reports) only evaluate data since 1950 or 1970. However, as emphasized by Chapter xxx, many of the worst extreme weather and climate events in U.S. history occurred in the first half of the 20<sup>th</sup> century and the 19<sup>th</sup> century. And if paleoclimate reconstructions are also considered, it becomes very difficult for an event to pass the detection thresholds of exceeding what is expected from natural variability, particularly if a reasonably sized geographic region is considered.~~

In spite of these concerns, the U.S. is presently considering something like the WWA, which is being investigated by a NASEM Panel on Attribution of Extreme Weather and Climate Events and their impacts (NASEM, 2025).

~~Extreme weather events can be extreme in terms of the magnitude of individual events, the frequency of events crossing some threshold, or clustering of extreme events. It needs to be acknowledged that extreme events are by definition rare, and short historical records (even century-long records) are insufficient for formulating meaningful statistics about return times and event likelihood.~~

Case studies from two recent high impact extreme events in the U.S. are provided to illustrate the challenges and ambiguities in attributing the frequency and intensity of extreme weather events to human-caused warming.

#### 6.4.1 Case study – 2021 Western North America heat wave

The 2021 Western North America heat wave was an extreme heat wave that affected much of Western North America in late June 2021. In particular, surface temperature records were set in Portland, OR (116°F; previous record 107°F) and Seattle, WA (108 °F; previous record 103°F) (Mass et al., 2024).

The WWA team garnered international headlines for their analysis and provided the following attribution statements (WWA, 2021; Philip et al., 2022):

- Based on observations and modeling, the occurrence of this heatwave was virtually impossible without human-caused climate change.
- The event is estimated to be about a 1 in 1000-year event in today's climate.
- The event would have been at least 150 times rarer without human-induced climate change.
- This heatwave was about 2°C hotter than it would have been if it had occurred at the beginning of the industrial revolution (when global mean temperatures were 1.2°C cooler than today).

But an important caveat to the first claim is that other researchers concluded, based on historical weather data, that while a heat wave of the magnitude observed was indeed virtually impossible without anthropogenic climate change, it was also virtually impossible *with* climate change. Bercos-Hickey (2022) noted “these temperatures were virtually impossible under any previously experienced meteorological conditions, with or without global warming.” McKinnon and Simpson (2022) stated “the most likely explanation remains that the weather event itself was ‘bad luck.’”. The 2023 Oregon Climate Assessment (Fleischman 2023) concluded the heat dome would have formed even without climate change and “There is no evidence that the highly unusual combination of weather features that drove the heat dome were made more likely by climate change, and climate models do not project an increase in the frequency of high-pressure ridges over the Pacific Northwest” (Fleischman 2023 p. 49).

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Mass et al (2024) summarizes the proximate sequence of compound events leading to the heat wave. There was a record-breaking midtropospheric ridge over the Pacific Northwest, forced by

a tropical disturbance in the western Pacific. This produced record-breaking midtropospheric temperatures, strong subsidence in the lower atmosphere, low-level easterly flow that produced downslope warming on regional terrain and the removal of cooler marine air, and an approaching low-level trough that enhanced downslope flow. The event occurred at a time of maximum solar insolation, and drier-than-normal soil moisture. Using a storyline approach, Mass et al. assessed that there is no trend in drought and dry soils in the Pacific Northwest; there is no evidence of global warming producing stronger ridges of high pressure, and no observed trend in heat waves or record temperatures in the region. They concluded that although anthropogenic warming may have contributed as much as 2°F to the magnitude of the event, there is little evidence of further amplification of the event from increasing greenhouse gases.

A more sophisticated statistical analysis of a model-based attribution study of this heat wave was conducted by Bercos-Hickey et al. (2022).— Because this event is a far outlier and far above the bounds of Generalized Extreme Value distributions fitted from historical data, they concluded that estimates of return times, quantitative changes in event magnitude and frequency, and probability of the extreme temperatures such as provided by the WWA are not accurate and should be interpreted as having low confidence. They found that hindcast attribution methods using an ensemble of regional climate models, combined with Pearl (2009) causal inferences, can provide limited and conditional information about the magnitude of the human influence on this heat wave — they provided a more highly constrained estimate that human activities caused a ~1.4°C–1.8°F increase in the daily maximum temperatures.

Zeder et al. (2023) also concluded that the methods employed by Philip et al. (2022) tend to overstate the rarity of extreme heat waves, leading to a biased perception of the effect of climate change on the heatwave event: “The tendency to overestimate the return period of observed extreme heatwave events may fuel the impression that seemingly impossible heatwave extremes are currently clustering at an unprecedented rate.”

The 2021 Western North America heatwave was a rare and unprecedented compound weather event, that broke century-old temperature records by as much as 9°F. While there is little doubt that anthropogenic global warming contributed to the probability and magnitude of the extreme temperatures, While the WWA team received worldwide publicity for their rapid attribution claims blaming anthropogenic climate change, subsequent peer-reviewed analysis showed that the rare uniqueness of the event challenges quantifying this influence by traditional event attribution methods. event was not made more probable by global warming.

~~Van Oldenborgh et al. (2022) summarize the challenges of attributing heat waves. A warming climate means that a fixed temperature threshold is passed more frequently, hence the probability of extreme heat increases. Land use changes, vegetation change, irrigation, air pollution, and other changes also drive changes in local and regional heatwaves trends. Sometimes these factors enhance heatwave intensity, but they can also counteract the effects of climate change. Temperature variability is unrealistic represented in many climate models, and does not stand up to standard quality assessments. Accordingly, heatwave attribution remains unreliable and a major scientific challenge in many regions. This is particularly true where the moisture budget is not well simulated, and where land surface changes have occurred.~~

**6.4.2 Case study – Hurricane Harvey rainfall** *IDON'T LOVE THIS EXAMPLE. DELETE? MAYBE SOMETHING ELSE?*

Hurricane Harvey made landfall in southern Texas on August 24, 2017 as a Category 4 hurricane. The primary damage from Harvey occurred after the storm had been downgraded to a tropical storm and stalled near the coastline with a stationary front along the TX/LA border, dropping torrential and unprecedented amounts of rainfall over Texas. Hurricane Harvey provides an informative example of the challenges of detection for a rare event, and also the complexity of extraneous factors that can influence such an event.

The first issue to consider is detection. Harvey set the record for most amount of rainfall from a continental U.S. landfalling hurricane (60 inches), going back at least to the 1880's when comprehensive records begin (Landsea, 2017). The previous top four rainfall producers for U.S. landfalling tropical cyclones were: 48 inches in Texas from Tropical Storm Amelia (1978), 45 inches in Florida from Hurricane Easy (1950), 45 inches in Florida from Tropical Storm Claudette (1979), and 40 inches in Texas from Tropical Storm Allison (2001). Looking more broadly at North Atlantic hurricanes that made landfall in Central American and the Caribbean, Roth (2017) identifies the following landfalling hurricanes that produced more rainfall than Harvey: 100 inches in Cuba from Hurricane Flora (1963), 96 inches in Jamaica from the November 1909 Hurricane, 63 inches in Nicaragua from Hurricane Mitch (1998), and 62 inches in Mexico from Hurricane Wilma (2005). Hurricane Harvey's rainfall arguably meets the detection criteria, whereby an attribution analysis is justified, although Harvey's rainfall was far from unprecedented from historic Atlantic hurricane landfalls.

In addressing the attribution of extreme rainfall from a landfalling hurricanes, there are several factors leading to excessive rainfall that aren't associated with temperature. Slow motion of the hurricane near landfall can lead to high amounts of local rainfall (e.g. Wilma – 2005; Harvey – 2017;). Mountains/hills near the coast magnify rainfall potential due to forced upslope flow (e.g. Mitch – 1998). Upper-level troughs and cold fronts can lead to excessive rainfall (e.g. Floyd – 1999). Horizontally large tropical cyclones have larger rain footprints, which can lead to excessive rainfall owing to the longer time frame over which rainfall falls at any one location.

The WWA attribution analysis of Hurricane Harvey's rainfall (GJ van Oldenburgh et al, 2017) found that human-caused climate change made the heavy rainfall associated with Hurricane Harvey roughly three times more likely and 15% more intense.

Several publications based on model simulations have concluded that as much as 40% of the rainfall from Hurricane Harvey was caused by human-caused global warming (Emanuel 2017; Risser and Wehner 2017). The rationale for these assessments was that prior to the beginning of summer of 2017, sea surface temperatures in the western Gulf of Mexico exceeded 86°F and ocean heat content was the highest on record in the Gulf of Mexico (Trenberth et al., 2018). However, El Niño–Southern Oscillation (ENSO) and Atlantic circulation patterns contributed to this elevated heat content.

Landsea (2017) summarizes the arguments for more rainfall from tropical cyclones traveling over a warmer ocean. Simple thermodynamic calculations suggest that the amount of rainfall in the tropical latitudes would increase by about 4% per °F of sea surface temperature increase.

Examining a 300-mile radius circle for nearly all of the rain implies that about 10% more total hurricane rainfall for a warming of 2-2.5°F. The Gulf of Mexico has warmed about 0.7°F since 1960. Even if it is assumed that all of this warming is due to manmade global warming, this suggests that roughly 3% of hurricane rainfall today can be reasonably attributed to manmade global warming. Hence, only about 2 inches of Hurricane Harvey's 60 inches can be linked to manmade global warming.

Aryal et al. (2018) examined the contribution of North Atlantic hurricanes to flooding and heavy rainfall across the continental U.S. Their analysis does not point to any significant changes in the magnitude or frequency of floods. They found that the North Atlantic Oscillation (NAO) plays a significant role in hurricane-related extreme rainfall along the U.S. East Coast, while ENSO is most strongly linked to the hurricane-related precipitation in Texas.

With regards to the rainfall associated with landfalling hurricanes, there is no clear signal of increasing rainfall owing to the complexity of the factors contributing to hurricane-induced rainfall.

## 6.5 Summary

There is an ongoing scientific debate around attribution methods, particularly in attributing extreme weather events to climate change. The IPCC has long cautioned that methods to establish causality in climate science are inherently uncertain and ultimately depend on expert judgement.

There are two areas of substantive criticism of the IPCC assessment of the causes of the recent warming: inadequate assessment of natural climate variability, and inappropriate statistical methods.

Detection of extreme weather events is challenged by their rarity, requiring a long data set and a choice of region and spatial scale to evaluate their occurrence against the background of natural weather and climate variability.

The most robust attribution statements for an extreme event relate to an incremental change (e.g. a temperature change in degrees or percent change in rainfall). Statements related to return times, quantitative changes in event magnitude and frequency, and probability of the extremes are not accurate owing to an inadequate amount of data, and are made with low confidence. There is no evidence in a change of weather or climate regime patterns from increasing greenhouse gases that would amplify or dampen extreme weather events, beyond basic thermodynamic considerations.

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## 8 Evidence on trends and attributable changes in extreme weather

Sources reviewed:

**SREX:** The IPCC *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (2012)

**AR5:** The IPCC *Fifth Assessment Report Working Group 1* (2013)

**AR6:** The IPCC *Sixth Assessment Report Working Group 1* (2021)

**NCA17:** The *US Climate Science Special Report of the Fourth National Climate Assessment* (2017) Volume I Chapter 6.

### 8.1 Flooding

SREX (p. 176)

In the United States and Canada during the 20th century and in the early 21st century, **there is no compelling evidence for climate-driven changes in the magnitude or frequency of floods.**

AR5 (p. 214)

AR4 WGI Chapter 3 (Trenberth et al., 2007) did not assess changes in floods but AR4 WGII concluded that **there was not a general global trend in the incidence of floods** (Kundzewicz et al., 2007). SREX went further to suggest that there was low agreement and thus *low confidence* at the global scale regarding changes in the magnitude or frequency of floods or even the sign of changes.

AR5 WGII assesses floods in regional detail accounting for the fact that trends in floods are strongly influenced by changes in river management (see also Section 2.5.2). Although the most evident flood trends appear to be in northern high latitudes, where observed warming trends have been largest, in some regions no evidence of a trend in extreme flooding has been found, for example, over Russia based on daily river discharge (Shiklomanov et al., 2007). Other studies for Europe (Hannaford and Marsh, 2008; Renard et al., 2008; Petrow and Merz, 2009; Stahl et al., 2010) and Asia (Jiang et al., 2008; Delgado et al., 2010) show evidence for upward, downward or no trend in the magnitude and frequency of floods, so that there is currently no clear and widespread evidence for observed changes in flooding except for the earlier springflow in snow-dominated regions (Seneviratne et al., 2012).

In summary, **there continues to be a lack of evidence and thus low confidence regarding the sign of trend in the magnitude and/or frequency of floods on a global scale.**

AR6 (Ch 11 p. 1568)

The SREX (Seneviratne et al., 2012) assessed *low confidence* for observed changes in the magnitude or frequency of floods at the global scale. This assessment was confirmed by the AR5 report (Hartmann et al., 2013). The SR15 (Hoegh-Guldberg et al., 2018) found increases in flood frequency and extreme streamflow in some regions, but decreases in other regions. **While the number of studies on flood trends has increased since the AR5 report, and there were also new analyses after the release of SR15 (Berghuijs et al., 2017; Blöschl et al., 2019; Gudmundsson et al., 2019), hydrological literature on observed flood changes is heterogeneous, focusing at regional and sub-regional basin scales, making it difficult to synthesise at the global and sometimes regional scales.**

In summary, the seasonality of floods has changed in cold regions where snowmelt dominates the flow regime in response to warming (*high confidence*). **Confidence about peak flow trends over past decades on the global scale is low, but there are regions experiencing increases**, including parts of Asia, southern South America, the northeast USA, northwestern Europe, and the Amazon, **and regions experiencing decreases**, including parts of the Mediterranean, Australia, Africa, and the southwestern USA.

US NCA17 pp. 240-41:

"The IPCC AR5 did not attribute changes in flooding to anthropogenic influence nor report detectable changes in flooding magnitude, duration, or frequency. Trends in extreme high values of streamflow are mixed across the United States. Analysis of 200 U.S. stream gauges indicates areas of both increasing and decreasing flooding magnitude but does not provide robust evidence that these trends are attributable to human influences...

The complex mix of processes complicates the formal attribution of observed flooding trends to anthropogenic climate change and suggests that additional scientific rigor is needed in flood attribution studies. As noted above, precipitation increases have been found to strongly influence changes in flood statistics. However, in U.S. regions, **no formal attribution of precipitation changes to anthropogenic forcing has been made so far, so indirect attribution of flooding changes is not possible. Hence, no formal attribution of observed flooding changes to anthropogenic forcing has been claimed.**"

## 8.2 Heatwaves

AR5 (p. 212 WG1)

Table 2.13 shows that there has been a *likely* increasing trend in the frequency of heatwaves since the middle of the 20th century in Europe and Australia and across much of Asia where there are sufficient data. However, confidence on a global scale is *medium* owing to lack of studies over Africa and South America but also in part owing to differences in trends depending on how heatwaves are defined (Perkins et al., 2012). Using monthly means as a proxy for heatwaves Coumou et al. (2013) and Hansen et al. (2012) indicate that record-breaking temperatures in recent decades substantially exceed what would be expected by chance but caution is required when making inferences between these studies and those that deal with multi-day events and/ or use more complex definitions for heatwave events. **There is also evidence in some regions that periods prior to the 1950s had more heatwaves (e.g., over the USA, the decade of the 1930s stands out and is also associated with extreme drought conditions** (Peterson et al., 2013) whereas conversely in other regions heatwave trends may have been underestimated owing to poor quality and/or consistency of data (e.g., Della-Marta et al. (2007a) over Western Europe; Kuglitsch et al. (2009, 2010) over the Mediterranean). Recent available studies also suggest that the number of cold spells has reduced significantly since the 1950s (Donat et al., 2013a, 2013c).

In summary, new analyses continue to support the AR4 and SREX conclusions that since about 1950 it is *very likely* that the numbers of cold days and nights have decreased and the numbers of warm days and nights have increased overall on the global scale, that is, for land areas with sufficient data. It is *likely* that such changes have also occurred across most of North America, Europe, Asia and Australia.

NCA17 (pp. 190-191)

Changes in warm extremes are more nuanced than changes in cold extremes. For instance, **the warmest daily temperature of the year increased in some parts of the West over the past century (Figure 6.3), but there were decreases in almost all locations east of the Rocky Mountains. In fact, all eastern regions experienced a net decrease** (Table 6.2), most notably the Midwest (about 2.2°F [1.2°C]) and the Southeast (roughly 1.5°F [0.8°C]). The decreases in the eastern half of [the] Nation, particularly in the Great Plains, are mainly tied to the unprecedented summer heat of the 1930s Dust Bowl era, which was exacerbated by land-surface feedbacks driven by springtime precipitation deficits and land mismanagement. However, anthropogenic aerosol forcing may also have reduced summer temperatures in the Northeast and Southeast from the early 1950s to the mid-1970s, and agricultural intensification may have suppressed the hottest extremes in the Midwest.

Since the mid-1960s, there has been only a very slight increase in the warmest daily temperature of the year (amidst large interannual variability). **Heat waves (6-day periods with a maximum temperature above the 90th percentile for 1961–1990) increased in frequency until the mid-1930s, became considerably less common through the mid-1960s, and increased in frequency again thereafter (Figure 6.4).** As with warm daily temperatures, heat wave magnitude reached a maximum in the 1930s.

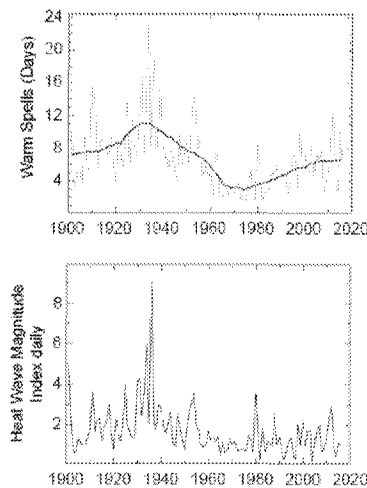


Figure 8.1: US Heat waves since 1900. Source: NCA17 Figure 6.4

AR6 (p. 1550)

In North America (Table 11.19), there is very robust evidence for a *very likely* increase in the intensity and frequency of hot extremes and decrease in the intensity and frequency of cold extremes for the whole continent, though there are substantial spatial and seasonal variations in the trends. Minimum temperatures display warming consistently across the continent, **while there are more contrasting trends in the annual maximum daily temperatures** in parts of the USA (Figure 11.9; Lee et al., 2014; van Oldenborgh et al., 2019; Dunn et al., 2020).

### 8.3 Extreme snowfall events

Note: extreme snowfall events in the US northeast are assessed in relation to winter Extratropical Cyclone (ETC) activity.

AR6 Ch 11. p. 1593

There is *high confidence* that snowfall associated with winter ETCs will decrease in the future, because increases in tropospheric temperatures lead to a lower proportion of precipitation falling as snow (O’Gorman, 2014; Rhoades et al., 2018; Zarzycki, 2018). However, there is *medium confidence* that extreme snowfall events associated with winter ETCs will change little in regions where snowfall will be supported in the future (O’Gorman, 2014; Zarzycki, 2018).

### 8.4 Extreme precipitation

SREX (p. 142)

Recent studies have updated the assessment of the AR4, with more regional results now available (Table 3-2). Overall, this additional evidence confirms that **more locations and studies show an increase than a decrease in extreme precipitation, but that there are also wide regional and seasonal variations**, and trends in many regions are not statistically significant (Table 3-2)... Based on station data from Canada, the United States, and Mexico, Peterson et al. (2008a) reported that heavy precipitation has been increasing over 1950-2004, as well as the average amount of precipitation falling on days with precipitation.

AR5 (pp. 213-14)

In summary, further analyses continue to support the AR4 and SREX conclusions that **it is likely that since 1951 there have been statistically significant increases in the number of heavy precipitation events (e.g., above the 95th percentile) in more regions than there have been statistically significant decreases, but there are strong regional and subregional variations in the trends**. In particular, many regions present statistically non-significant or negative trends, and, where seasonal changes have been assessed, there are also variations between seasons (e.g., more consistent trends in winter than in summer in Europe). The overall most consistent trends towards heavier precipitation events are found in central North America (very likely increase) but assessment for Europe shows likely increases in more regions than decreases.

AR6 (p. 1560)

In North America, there is robust evidence that the magnitude and intensity of extreme precipitation has *very likely* increased since the 1950s. Both [one-day maxima] and [5-day maxima] have significantly increased in North America during 1950-2018 (Sun et al., 2020, also Figure 11.13). There is, however, regional diversity. **In Canada, there is a lack of detectable trends in observed annual maximum daily (or shorter duration) precipitation (Shephard et al., 2014; Mekis et al., 2015; Vincent et al., 2018).**

NCA17 pp. 213-14:



Detectability of trends (compared to internal variability) for a number of precipitation metrics over the continental United States has been examined; **however, trends identified for the U.S. regions have not been clearly attributed to anthropogenic forcing**. One study concluded that increasing precipitation trends in some north-central U.S. regions and the extreme annual anomalies there in 2013 were at least partly attributable to the combination of anthropogenic and natural forcing... **Based on current evidence, it is concluded that detectable but not attributable increases in mean precipitation have occurred over parts of the central United States**. Formal detection-attribution studies indicate a human contribution to extreme precipitation increases over the continental United States, but confidence is *low* based on those studies alone due to the short observational period, high natural variability, and model uncertainty.

In summary, based on available studies, it is concluded that for the continental United States there is *high confidence* in the detection of extreme precipitation increases, while there is *low confidence* in attributing the extreme precipitation changes purely to anthropogenic forcing.

### Other sources:

US long term data (NOAA) shows an insignificantly increasing tendency toward extreme wetness (+0.001% per year)

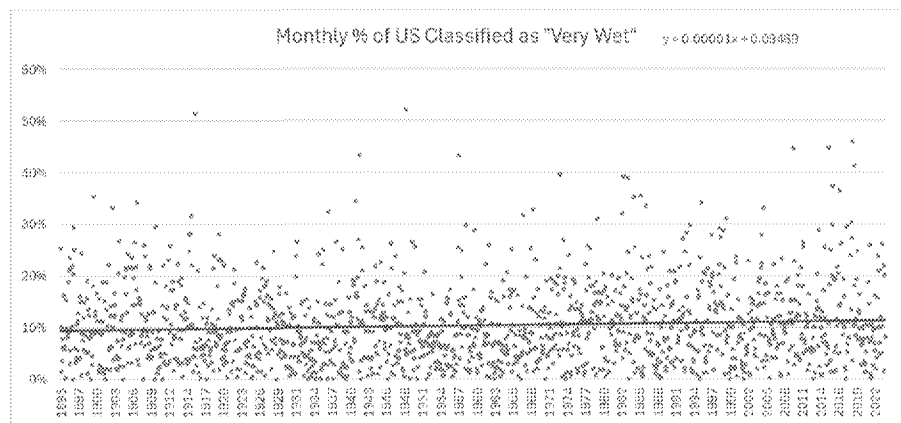


Figure 8.2: Long term US wetness (%). Source: NOAA [ [HYPERLINK "https://www.ncei.noaa.gov/access/monitoring/uspa/wet-dry/0"](https://www.ncei.noaa.gov/access/monitoring/uspa/wet-dry/0) ]

A deficiency of the NCA4 Report is that it focused only on the 1901-2016 interval. In many locations the trends are not consistent when examining other time intervals. McKittrick and Christy (2020) took a sample of 20 US locations in the Southeast and Pacific coast. While measures of average and extreme precipitation increased slightly over the NCA4’s 1901-2016 time interval, the available data in question go back to the mid-1800s and in many US locations the pre-1900 interval was marked by high levels of precipitation. McKittrick and Christy found that over the full data sample the trends were not necessarily uniform. Specifically the Southeast also showed a significant increase in the number of 1-day 99th percentile exceedances (the NCA4 metric for heavy rainfall

events) over 1901-2016, but over the full record spanning 1872-2017 the trend is not significant, and in the post-1978 period the trend is actually slightly negative:

“Over the 1901–2017 interval upward trends in some measures of average and extreme precipitation appear, but they are not consistently significant and in the full records back to 1872 they largely disappear. They also disappear or reverse in the post-1978 portion of the data set, which is inconsistent with them being responses to enhanced greenhouse gas forcing. We conclude that natural variability is likely the dominant driver of historical changes in precipitation and hence drought dynamics in the US SE and PC.... Summing up, while trends can be identified on some time spans, on the longest samples the trends are not significant, nor are they significant over the shorter interval of enhanced greenhouse forcing, and the proxy data exhibit long term persistence. Taken together these findings are consistent with the view that natural variability is likely the dominant factor in historical US precipitation changes through to the present time.”

## 8.5 Tornadoes and severe convective storms

IPCC AR6 Sct. 11.7.3, p. 1594

Severe convective storms are convective systems that are associated with extreme phenomena such as tornadoes, hail, heavy precipitation (rain or snow), strong winds, and lightning.

The assessment of changes in severe convective storms in SREX (Chapter 3, Seneviratne et al., 2012) and AR5 (Chapter 12, Collins et al., 2013) is limited and focused mainly on tornadoes and hail storms. The SREX assessed that there is *low confidence* in observed trends in tornadoes and hail because of data inhomogeneities and inadequacies in monitoring systems. Subsequent literature assessed in the Climate Science Special Report (Kossin et al., 2017) led to the assessment of the observed tornado activity over the 2000s in the USA, with a decrease in the number of days per year with tornadoes and an increase in the number of tornadoes on these days (*medium confidence*). However, there is *low confidence* in past trends for hail and severe thunderstorm winds. Climate models consistently project environmental changes that would support an increase in the frequency and intensity of severe thunderstorms that combine tornadoes, hail, and winds (*high confidence*), but there is *low confidence* in the details of the projected increase.

Trends: p. 1595

In summary, because the definition of severe convective storms varies depending on the literature and the region, it is not straightforward to make a synthesizing view of observed trends in severe convective storms in different regions. In particular, observational trends in tornadoes, hail, and lightning associated with severe convective storms are not robustly detected due to insufficient coverage of the long-term observations. There is *medium confidence* that the mean annual number of tornadoes in the USA has remained relatively constant, but their variability of occurrence has increased since the 1970s, particularly over the 2000s, with a decrease in the number of days per year, and an increase in the number of tornadoes on these days (*high confidence*). Detected tornadoes have also increased in Europe, but the trend depends on the density of observations.

Attribution: p. 1596

It is extremely difficult to detect differences in time and space of severe convective storms (Kunkel et al., 2013). Although some ingredients that are favourable for severe thunderstorms have increased over the years, others have not; thus, overall, changes in the frequency of environments favourable for severe thunderstorms have not been statistically significant... For hailstorms, such as those that caused disasters in the USA in 2018, detection of the role of climate change in changing hail storms is more difficult, because hail storms are not, in general, directly simulated by convection-permitting models and not adequately represented by the environmental parameters of coarse-resolution GCMs (Mahoney, 2020).

In summary, it is extremely difficult to detect and attribute changes in severe convective storms. There is limited evidence that extreme precipitation associated with severe convective storms has increased in some cases.

## 8.6 Hurricanes and Tropical Cyclones

SREX (p. 159):

**There have been no significant trends observed in global tropical cyclone frequency records, including over the present 40-year period of satellite observations** (e.g., Webster et al., 2005). Regional trends in tropical cyclone frequency have been identified in the North Atlantic, but the fidelity of these trends is debated (Holland and Webster, 2007; Landsea, 2007; Mann et al., 2007a). Different methods for estimating undercounts in the earlier part of the North Atlantic tropical cyclone record provide mixed conclusions (Chang and Guo, 2007; Mann et al., 2007b; Kunkel et al., 2008; Vecchi and Knutson, 2008). Regional trends have not been detected in other oceans (Chan and Xu, 2009; Kubota and Chan, 2009; Callaghan and Power, 2011). **It thus remains uncertain whether any observed increases in tropical cyclone frequency on time scales longer than about 40 years are robust**, after accounting for past changes in observing capabilities (Knutson et al., 2010).

AR5 (pp. 216-17):

**Current data sets indicate no significant observed trends in global tropical cyclone frequency** over the past century and it remains uncertain whether any reported long-term increases in tropical cyclone frequency are robust, after accounting for past changes in observing capabilities (Knutson et al., 2010). **No robust trends in annual numbers of tropical storms, hurricanes and major hurricanes counts have been identified** over the past 100 years in the North Atlantic basin. Measures of land-falling tropical cyclone frequency (Figure 2.34) are generally considered to be more reliable than counts of all storms which tend to be strongly influenced by those that are weak and/or short lived. Callaghan and Power (2011) find a statistically significant decrease in Eastern Australia land-falling tropical cyclones since the late 19th century although including 2010/2011 season data this trend becomes non-significant (i.e., a trend of zero lies just inside the 90% confidence interval). Significant trends are not found in other oceans on shorter time scales (Chan and Xu, 2009; Kubota and Chan, 2009; Mohapatra et al., 2011; Weinkle et al., 2012), although Grinsted et al. (2012) find a significant positive trend in eastern USA using tide-gauge data from 1923–2008 as a proxy for storm surges associated with land-falling hurricanes. Differences between tropical cyclone studies highlight the challenges that still lie ahead in assessing long-term trends.

In summary, this assessment does not revise the SREX conclusion of *low confidence* that any reported long-term (centennial) increases in tropical cyclone activity are robust, after accounting for past changes in observing capabilities. More recent assessments indicate that **it is *unlikely* that annual numbers of tropical storms, hurricanes and major hurricanes counts have increased over the past 100 years in the North Atlantic basin.** Evidence, however, is for a virtually certain increase in the frequency and intensity of the strongest tropical cyclones since the 1970s in that region.

AR6 (p. 1585)

**There is *low confidence* in most reported long-term (multidecadal to centennial) trends in TC frequency- or intensity-based metrics due to changes in the technology used to collect the best-track data.** This should not be interpreted as implying that no physical (real) trends exist, but rather as indicating that either the quality or the temporal length of the data is not adequate to provide robust trend detection statements, particularly in the presence of multidecadal variability.

There are previous and ongoing efforts to homogenize the best-track data (Elsner et al., 2008; Kossin et al., 2013, 2020; Choy et al., 2015; Landsea, 2015; Emanuel et al., 2018) and there is substantial literature that finds positive trends in intensity-related metrics in the best-track during the “satellite period”, which is generally limited to the past ~40 years (Kang and Elsner, 2012; Kishtawal et al., 2012; Kossin et al., 2013, 2020; Mei and Xie, 2016; Zhao et al., 2018; Tauvale and Tsuboki, 2019). **When best-track trends are tested using homogenized data, the intensity trends generally remain positive, but are smaller in amplitude** (Kossin et al., 2013; Holland and Bruyère, 2014). **Kossin et al. (2020) extended the homogenized TC intensity record to the period 1979–2017 and identified significant global increases in major TC exceedance probability of about 6% per decade.** In addition to trends in TC intensity, there is evidence that TC intensification rates and the frequency of rapid intensification events have increased within the satellite era (Kishtawal et al. 2012; Balaguru et al., 2018; Bhatia et al., 2018). The increase in intensification rates is found in the best-track as well as the homogenized intensity data.

**A subset of the best-track data corresponding to hurricanes that have directly impacted the United States since 1900 is considered to be reliable, and shows no trend in the frequency of U.S. landfall events (Knutson et al., 2019).**

The **Underlined** text referenced a study (Kossin et al. 2020) that later retracted a portion of its findings. The authors assembled a data set on global TC incidence spanning 1979 to 2017. They claimed that the global fraction of TCs reaching major status (Cat 3–5) rose from 27% in the 1979–1997 interval to 31% in the 1998–2017 interval and the difference was statistically significant. Closer examination of their results however (Table 1) showed a significant increase was only observed in the North Atlantic (18% to 34%) whereas in every other basin (Eastern Pacific, Western Pacific, North Indian, South Indian, South Pacific) the differences were not statistically significant. They estimated that the global increase in the probability of a hurricane becoming major rose by an average of 6% per decade.

The next problem with their claim is that, unlike other basins, hurricane strength records for the North Atlantic and the Western Pacific go back to 1950 and the whole record does not show an increase in either total or major TCs:

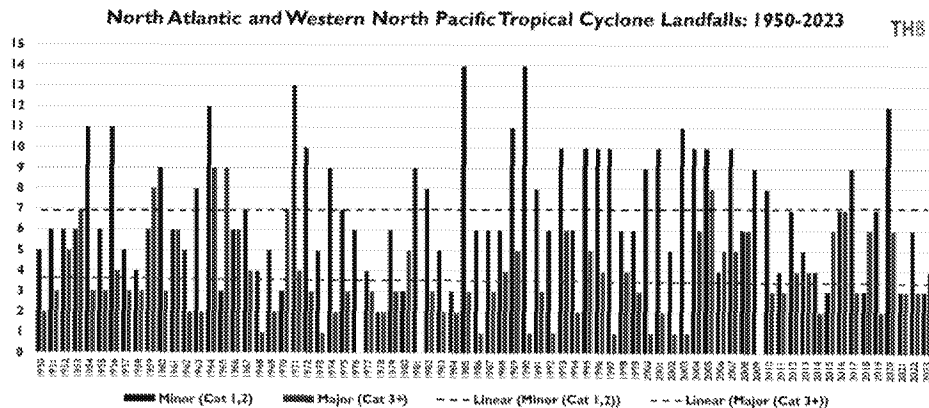


Figure 8.3. Tropical Cyclone Landfalls. Source: [ [HYPERLINK](https://rogerpielkejr.substack.com/p/global-tropical-cyclones) "https://rogerpielkejr.substack.com/p/global-tropical-cyclones"]

After the Kossin paper was published a reader named Greg Kent examined the data and found that Kossin et al. had made elementary tabulation errors which needed to be corrected. They issued a Correction (<https://www.pnas.org/doi/10.1073/pnas.2021573117>). The main one was that the global probability of observing a major TC was now 34% in the 1979 to 1997 interval rising to 37% in the later period and the evidence for statistical significance was now weaker, although the authors claimed that the correction did not affect their conclusions.

Kent also showed that within the Kossin et al. data set, only Category 3 hurricanes showed an increase in occurrent probability; Cat4 storms were unchanged and Cat5 storms became *less* likely.

#### 8.7 Other sources

The total number of hurricanes is not increasing and in many basins is decreasing. Consequently even if the fraction that becomes major goes up, the total number of major storms doesn't necessarily go up as well. As shown in the Climate Atlas data set maintained by Dr. Ryan Maue neither total hurricanes nor major ones have become more common since 1980, indeed both have trended down:

Global Major Hurricane Frequency -- 12 month running sums -- @RyanMaue  
 Updated December 31, 2023

Last 30-years: 45.7 yr | 24.4 yr

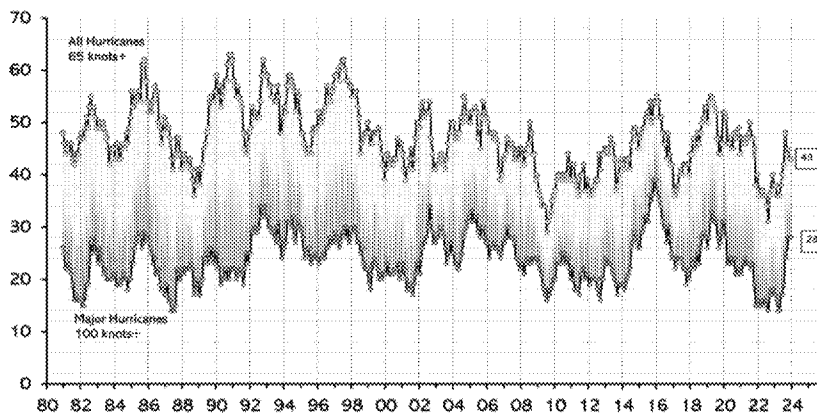


Figure 8.4: Global hurricane frequency. Source: Maue (2024)

A metric that combines the number and frequency of TCs is the Accumulated Cyclone Energy. It is computed by Phil Klotzbach at Colorado State University:

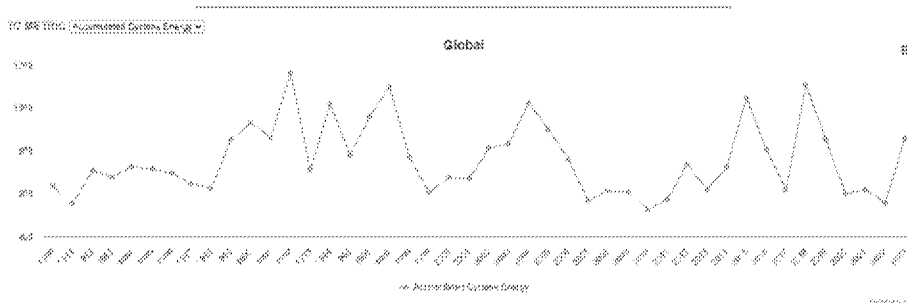


Figure 8.5: Global Accumulated Cyclone Energy. Source: Klotzbach (2025)

[ HYPERLINK "<https://tropical.atmos.colostate.edu/Realtime/index.php?arch&loc=global>"]

As is clear, it is also not increasing and since 1990 has trended down slightly.

Climate models show declining hurricane formation rates in a warming climate (Chand et al. 2022). Climate models also project fewer Tropical Cyclones under future global warming, and even though they increase in strength, the annual averages of rainfall maxima decline (Stansfield et al. 2020).

## 8.8 Wildfires

The IPCC has not provided an assessment of wildfires.

### Other sources

As shown in Figures 8.6 and 8.7 global wildfire measured by European Space Agency peaked over a decade ago and show downward trends since.

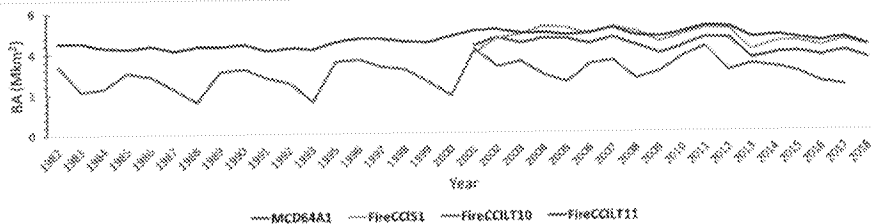


Figure 8.6: Global wildfire 1982-2018. Source: Copied from Oton et al. (2021). Note: the different coloured lines represent different data products based on satellites and algorithms used.

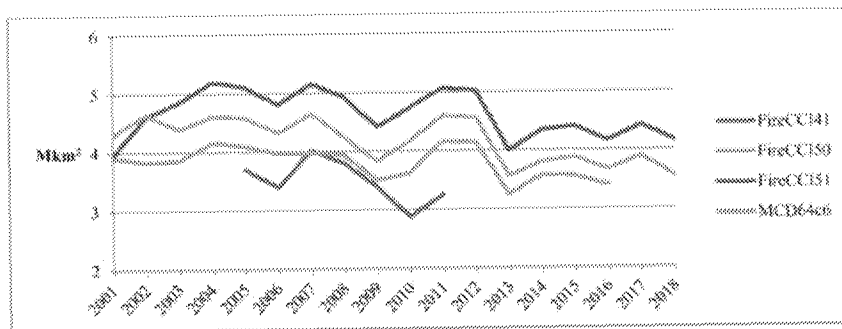


Figure 8.7: Global wildfire 2001-2018. Source: Copied from Lizundia-Loiola et al. (2021). Note: the different coloured lines represent different data products based on satellites and algorithms used

Also see Doerr SH and Santin C. (2016) :

#### Abstract:

Wildfire has been an important process affecting the Earth's surface and atmosphere for over 350 million years and human societies have coexisted with fire since their emergence. Yet many consider wildfire as an accelerating problem, with widely held perceptions both in the media and scientific papers of increasing fire occurrence, severity and resulting losses. However, important exceptions aside, the quantitative evidence available does not support these perceived overall trends. Instead, global area burned appears to have overall declined over past decades, and there is increasing evidence that there is less fire in the global landscape today than centuries ago. Regarding fire severity, limited data are available. For the western USA, they indicate little change overall, and also that area burned at high severity has overall declined compared to pre-European settlement. Direct fatalities from fire and economic losses also show no clear

trends over the past three decades. Trends in indirect impacts, such as health problems from smoke or disruption to social functioning, remain insufficiently quantified to be examined. Global predictions for increased fire under a warming climate highlight the already urgent need for a more sustainable coexistence with fire. The data evaluation presented here aims to contribute to this by reducing misconceptions and facilitating a more informed understanding of the realities of global fire.

US data from 1926 to 2023 are shown in Figure 8.8.

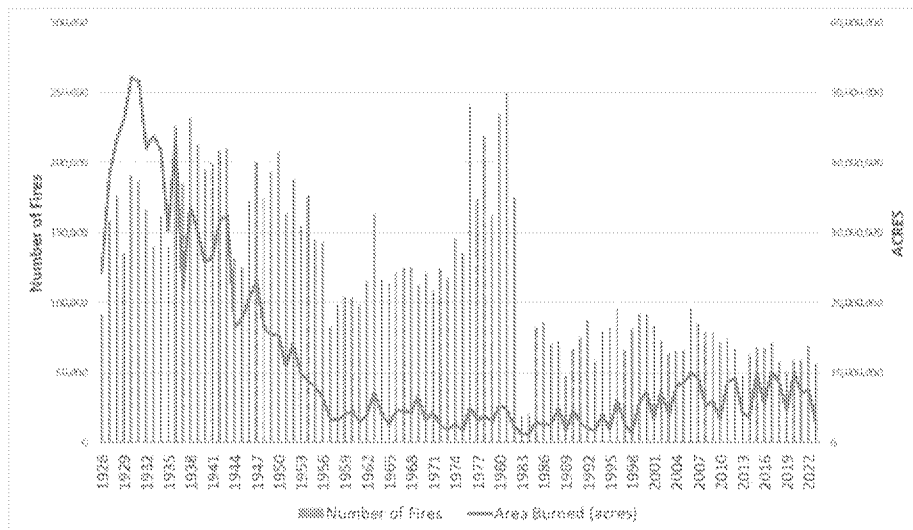


Figure 8.8: US wildfires 1926 to 2023. Source:

[[https://web.archive.org/web/20200212033452/https://www.nifc.gov/fireInfo/fireInfo\\_stats\\_totalFires.html](https://web.archive.org/web/20200212033452/https://www.nifc.gov/fireInfo/fireInfo_stats_totalFires.html)] (pre-2017)  
[[HYPERLINK "https://www.nifc.gov/fire-information/statistics/wildfires"](https://www.nifc.gov/fire-information/statistics/wildfires)] (2018-2023)

Note the NIFC has removed the pre-1960 data from its current website. They claim it is because measurement methods changed after 1960. This explanation seems inadequate since agencies blend temperature and extreme weather data series in other context when measurement systems changed. In this case if anything measurement of wildfires has improved since the early 20<sup>th</sup> century so any bias will be towards understating wildfire counts in the earlier period. Nonetheless just focusing on the post-1985 interval the number of fires is not increasing. The area burned did increase but only until about 2007.

Marlon et al. (2012) used sedimentary charcoal layers to reconstruct fire history of western US back 1400 years. They also fit a model to predict expected fire activity as a function of climatic conditions. The results are summarized in the Figure below (from Figure 2 in their paper).



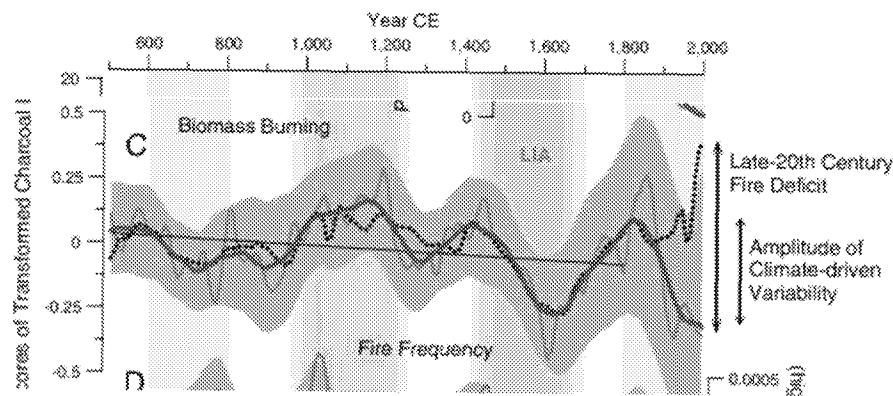


Figure 8.9: Fire frequency and fire deficit in the US. Source: Copied from Marlon et al. (2012)

In their figure the red line shows the smoothed charcoal record and the black dotted line shows the predicted charcoal record based on the statistical model. The gap at the end is the current Fire Deficit, covering the 20<sup>th</sup> century. In other words, however much fire was observed in the 20<sup>th</sup> century it was far less than what would have been observed in previous centuries based on the climatic conditions. The authors comment:

The fire deficit identified here might appear to contrast with observations of recent increases in western U.S. fire activity and also to the well established fire-climate interactions documented across the region. These apparent differences can be reconciled by explicit consideration of the time scale of the variations. We show that mean or baseline levels of biomass burned and fire frequency decreased substantially during the past century compared with previous centuries; **the recent increase in “fire activity” (i.e., large-wildfire occurrence) is therefore occurring during a period of unusually low levels of biomass burning.** ... During the past two centuries, however, centennial-scale changes in biomass burned and fire frequency however, are decoupled from climate due to the strong human influences on forests and fires. (p. E541)

Parks et al. (2025) has confirmed that despite the recent increase in wildfire burn area in North America, relative to historical wildfire regimes there remains a significant wildfire deficit.

## 8.9 Droughts

**US NCA17 REPORT** (Ch. 8, Wehner et al. 2017)

p. 231:

Recent droughts and associated heat waves have reached record intensity in some regions of the United States; however, by geographical scale and duration, the Dust Bowl era of the 1930s remains the benchmark drought and extreme heat event in the historical record (very high confidence). **While by some measures drought has decreased over much of the continental United States in association with long-term increases in precipitation,**

**neither the precipitation increases nor inferred drought decreases have been confidently attributed to anthropogenic forcing.**

The human effect on recent major U.S. droughts is complicated. Little evidence is found for a human influence on observed precipitation deficits, but much evidence is found for a human influence on surface soil moisture deficits due to increased evapotranspiration caused by higher temperatures. (*High confidence*)

p. 233 (Note Fig 7.1 shows past increases in precipitation while Figure 7.5 shows projected future changes by season)

Drought is, of course, directly connected to seasonal precipitation totals. Figure 7.1 shows detectable observed recent changes in seasonal precipitation. In fact, the increases in observed summer and fall precipitation are at odds with the projections in Figure 7.5. **As a consequence of this increased precipitation, drought statistics over the entire CONUS have declined.**

SREX (p. 170)

**From a paleoclimate perspective recent droughts are not unprecedented, with severe ‘megadroughts’ reported in the paleoclimatic record for Europe, North America, and Australia** (Jansen et al., 2007). Recent studies extend this observation to African and Indian droughts (Sinha et al., 2007; Shanahan et al., 2009): much more severe and longer droughts occurred in the past centuries with widespread ecological, political, and socioeconomic consequences. Overall, these studies confirm that in the last millennium several extreme droughts have occurred (Breda and Badeau, 2008; Kallis, 2008; Büntgen et al., 2010).

**In North America, there is *medium confidence* that there has been an overall slight tendency toward less dryness** (wetting trend with more soil moisture and runoff; Table 3-2), although analyses for some subregions also indicate tendencies toward increasing dryness. This assessment is based on several lines of evidence, including simulations with different hydrological models as well as PDSI and CDD estimates (Alexander et al., 2006; Andreadis and Lettenmaier, 2006; van der Schrier et al., 2006a; Kunkel et al., 2008; Sheffield and Wood, 2008a; Dai, 2011).

**The most severe droughts in the 20th century have occurred in the 1930s and 1950s**, where the 1930s Dust Bowl was most intense and the 1950s drought most persistent (Andreadis et al., 2005) in the United States, while in Mexico the 1950s and late 1990s were the driest periods. Recent regional trends toward more severe drought conditions were identified over southern and western Canada, Alaska, and Mexico, with subregional exceptions (Dai, 2011).

SREX (p. 172)

**Overall, though new studies have furthered the understanding of the mechanisms leading to drought, there is still relatively limited evidence to provide an attribution of observed changes**, in particular given the issues associated with the availability of observational data (Section 3.2.1) and the definition and computation of drought indicators (Box 3-3). This latter point was mostly identified in post-AR4 studies (Box 3-3). Moreover, regions where consistent increases in drought are identified (see ‘Observed Changes’) are only partly consistent with those where projections indicate an enhancement of drought conditions in coming decades (see next paragraphs). We thus assess that there is *medium*

*confidence* (see also Section 3.1.5) that anthropogenic influence has contributed to some changes in the drought patterns observed in the second half of the 20<sup>th</sup> century, based on its attributed impact on precipitation and temperature changes (though temperature can only be indirectly related to drought trends; see Box 3-3). However **there is low confidence in the attribution of changes in droughts at the level of individual regions.**

AR5 (pp. 214-215)

Based on evidence since AR4, SREX concluded that there were not enough direct observations of dryness to suggest high confidence in observed trends globally, although there was *medium confidence* that since the 1950s some regions of the world have experienced more intense and longer droughts. The differences between AR4 and SREX are due primarily to analyses post-AR4, differences in how both assessments considered drought and updated IPCC uncertainty guidance.

Because drought is a complex variable and can at best be incompletely represented by commonly used drought indices, discrepancies in the interpretation of changes can result. For example, Sheffield and Wood (2008) found decreasing trends in the duration, intensity and severity of drought globally. Conversely, Dai (2011a,b) found a general global increase in drought, although with substantial regional variation and individual events dominating trend signatures in some regions (e.g., the 1970s prolonged Sahel drought and the 1930s drought in the USA and Canadian Prairies). Studies subsequent to these continue to provide somewhat different conclusions on trends in global droughts and/or dryness since the middle of the 20th century (Sheffield et al., 2012; Dai, 2013; Donat et al., 2013c; van der Schrier et al., 2013).

**In summary, the current assessment concludes that there is not enough evidence at present to suggest more than low confidence in a global-scale observed trend in drought or dryness (lack of rainfall) since the middle of the 20th century,** owing to lack of direct observations, geographical inconsistencies in the trends, and dependencies of inferred trends on the index choice. Based on updated studies, AR4 conclusions regarding global increasing trends in drought since the 1970s were probably overstated. However, it is *likely* that the frequency and intensity of drought has increased in the Mediterranean and West Africa and decreased in central North America and north-west Australia since 1950.

AR6 (Drought, Observed trends, Section 11.6.2, pp. 1573-75)

p. 1573

Strong precipitation deficits have been recorded in recent decades in the Amazon (2005, 2010), south-western China (2009–2010), south-western North America (2011–2014), Australia (1997–2009), California (2014), the middle East (2012–2016), Chile (2010–2015), the Great Horn of Africa (2011), among others (van Dijk et al., 2013; Mann and Gleick, 2015; Rowell et al., 2015; Marengo and Espinoza, 2016; Dai and Zhao, 2017; Garreaud et al., 2017, 2020; Marengo et al., 2017; Brito et al., 2018; Cook et al., 2018). **Global studies generally show no significant trends in SPI time series** (Orlowsky and Seneviratne, 2013; Spinoni et al., 2014), **and in derived drought frequency and severity data** (Spinoni et al., 2019), with very few regional exceptions (Section 11.9 and Figure 11.17).

p. 1574

For AR6 regions, several studies suggest an increase in the frequency and areal extent of soil moisture deficits, with examples in East Asia (Cheng et al., 2015; Y. Qin et al., 2015; Jia et al., 2018), Western and Central Europe (Trnka et al., 2015b), and the Mediterranean (Hanel et al., 2018; Moravec et al., 2019; Markonis et al., 2021). **Nonetheless, some analyses also show no long-term trends in soil drying in some AR6 regions – for example, in Eastern North America (Park Williams et al., 2017) and Central North America (Seager et al., 2019), as well as in North Eastern Africa (Kew et al., 2021).**

There is evidence based on streamflow records of increased hydrological droughts in East Asia (D. Zhang et al., 2018) and southern Africa (Gudmundsson et al., 2019). **In areas of Western and Central Europe and Northern Europe, there is no evidence of changes in the severity of hydrological droughts since 1950** based on flow reconstructions (Caillouet et al., 2017; Barker et al., 2019) and observations (Vicente-Serrano et al., 2019). **In North America, depending on the methods, datasets and study periods, there are differences between studies that suggest an increase (Shukla et al., 2015; Udall and Overpeck, 2017) versus a decrease in hydrological drought frequency (Mo and Lettenmaier, 2018), but in general there is strong spatial variability** (Poshtiri and Pal, 2016). Streamflow observation reference networks of near-natural catchments have also been used to isolate the effect of climate trends on hydrological drought trends in a few regions, but these show limited trends in Northern Europe and Western and Central Europe (Stahl et al., 2010; Bard et al., 2015; Harrigan et al., 2018), North America (Dudley et al., 2020) and most of Australia, with the exception of Eastern and Southern Australia (X.S. Zhang et al., 2016).

p. 1575

**Few AR6 regions show observed increases in meteorological drought** (Section 11.9), mostly in Africa and South America (NES: *high confidence*; WAF, CAF, ESAF, SAM, SWS, SSA, SAS: *medium confidence*); a few others show a decrease (WSB, ESB, NAU, CAU, NEU, CNA: *medium confidence*). There are stronger signals indicating observed increases in agricultural and ecological drought (Section 11.9), which highlights the role of increased [evapotranspiration], driven by increased [Atmospheric Evaporative Demand], for these trends (Sections 11.6.2.3, 11.6.2.5). Past increases in agricultural and ecological droughts are found on all continents and several regions (WAF, CAF, WSAF, ESAF, WCA, ECA, EAS, SAU, MED, WCE, NES: *medium confidence*), while decreases are found only in one AR6 region (NAU: *medium confidence*). The more limited availability of datasets makes it more difficult to assess historical trends in hydrological drought at regional scale (Section 11.9). Increasing (MED: *high confidence*; WAF, EAS, SAU: *medium confidence*) and decreasing (NEU, SES: *medium confidence*) trends in hydrological droughts have only been observed in a few regions.

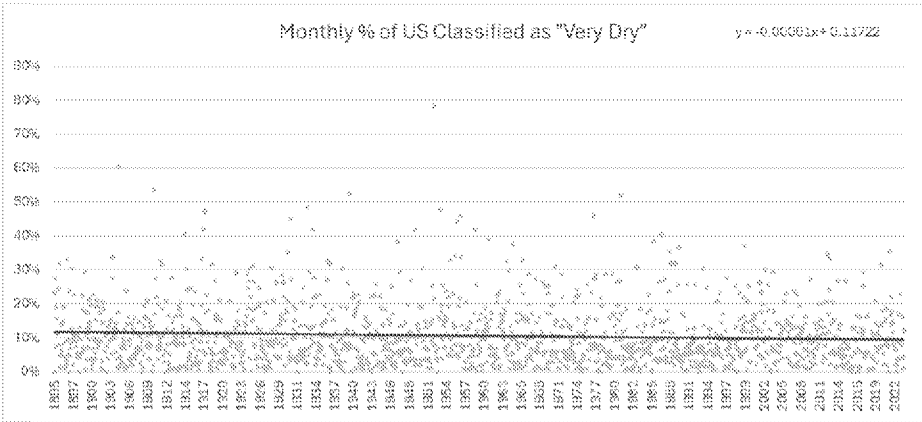
AR6 on Attribution (p. 1577)

There are only two AR6 regions in which there is at least *medium confidence* that human-induced climate change has contributed to changes in meteorological droughts (Section 11.9). In South-western South America (SSW), there is *medium confidence* that human-induced climate change has contributed to an increase in meteorological droughts (Boisier et al., 2016; Garreaud et al., 2020), while in Northern Europe (NEU), there is *medium confidence* that it has contributed to a decrease in meteorological droughts (Gudmundsson and Seneviratne, 2016) (Section 11.9). **In other AR6 regions, there is inconclusive evidence in the attribution of long-term trends, but a human contribution to single meteorological events or subregional trends has been identified in some instances...**

In North America, the human influence on precipitation deficits is complex (Wehner et al., 2017), with low confidence in the attribution of long-term changes in meteorological drought in AR6 regions.

Other sources

As shown in Figure 8.10 US long term data (NOAA) shows insignificantly declining tendency toward extreme dryness (-0.001% per year)



**Figure 8.10:** US dryness (%) 1895—2023. Source: NOAA [ [HYPERLINK "https://www.ncei.noaa.gov/access/monitoring/uspa/wet-dry/0"](https://www.ncei.noaa.gov/access/monitoring/uspa/wet-dry/0)]

Kogan et al. (2020) examines a 38 year high-resolution satellite-based drought measure and concludes that global drought has not intensified and is not connected to climate change: “it is possible to state firmly that global and main grain countries’ drought area and intensity trends have not been following global climate warmings since 1980’s.”

8.10 Summary: IPCC Assessment of signal emergence in extreme weather types (IPCC WG1 Table 12.12)

| Climate Impact Driver Type | Climate Impact Driver Category         | Already Emerged in the Historical Record? | Emerging by 2050 in Most Extreme CO2 Emissions Scenario? | Emerging by 2100 in Most Extreme CO2 Emissions Scenario? |
|----------------------------|----------------------------------------|-------------------------------------------|----------------------------------------------------------|----------------------------------------------------------|
| Heat & Cold                | Average air temperature                | YES in most regions                       | YES                                                      | YES                                                      |
|                            | More heat extremes                     | YES in most regions                       | YES in land regions                                      | YES                                                      |
|                            | Fewer cold extremes                    | YES in a few regions                      | YES in many regions                                      | YES                                                      |
|                            | Less frost                             | NO                                        | NO                                                       | NO                                                       |
| Wet & Dry                  | Average Precip. (Increase or Decrease) | NO                                        | YES (incr) YES (decr)                                    | YES (incr) YES (decr)                                    |
|                            | River flooding                         | NO                                        | NO                                                       | NO                                                       |
|                            | Heavy precip & pluvial flood           | NO                                        | NO                                                       | YES in a few regions                                     |

|              |                                   |                          |                      |                 |
|--------------|-----------------------------------|--------------------------|----------------------|-----------------|
|              | Landslide                         | NO                       | NO                   | NO              |
|              | Aridity                           | NO                       | NO                   | NO              |
|              | Hydrologic Drought                | NO                       | NO                   | NO              |
|              | Agricultural & ecological drought | NO                       | NO                   | NO              |
|              | Fire weather                      | NO                       | NO                   | NO              |
| Wind         | Average wind speed                | NO                       | NO                   | NO              |
|              | Severe wind storm                 | NO                       | NO                   | NO              |
|              | Tropical cyclone                  | NO                       | NO                   | NO              |
|              | Sand and dust storm               | NO                       | NO                   | NO              |
| Snow and Ice | Snow, glacier & ice sheet         | NO                       | YES in a few regions | YES Arctic snow |
|              | Permafrost                        | YES                      | YES                  | YES             |
|              | Lake & river ice                  | NO                       | YES                  | YES             |
|              | Arctic sea ice                    | YES                      | YES                  | YES             |
|              | Antarctic sea ice                 | NO                       | YES                  | YES             |
|              | Heavy snowfall and ice storm      | NO                       | NO                   | NO              |
|              | Hail                              | NO                       | NO                   | NO              |
|              | Snow avalanche                    | NO                       | NO                   | NO              |
| Coastal      | Relative sea level                | NO                       | YES                  | YES             |
|              | Coastal flood                     | NO                       | NO                   | NO              |
|              | Coastal erosion                   | NO                       | NO                   | NO              |
| Open Ocean   | Average ocean temperature         | YES                      | YES                  | YES             |
|              | Marine heat wave                  | NO                       | NO                   | NO              |
|              | Ocean acidity                     | NO                       | YES                  | YES             |
|              | Ocean salinity                    | YES                      | YES                  | YES             |
|              | Dissolved oxygen                  | YES (Pacific & S. Ocean) | YES                  | YES             |
| Other        | Air pollution weather             | NO                       | NO                   | NO              |
|              | Solar or IR radiation at surface  | NO                       | NO                   | NO              |

**Table 8.1.** IPCC AR6 summary of the probable emergence of an anthropogenic signal above natural climate variability for all global or regional “climate impact drivers” (CIDs) of concern for humans and ecosystems in response to increasing atmospheric greenhouse gas concentrations (primarily CO<sub>2</sub>). Source: Table adapted from report of Working Group I, Table 12.12). Red = high confidence; yellow = medium confidence; green = no anthropogenic signal detectable above natural variability (50% confidence).

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Note that for all weather variables, *only direct temperature-related effects have been observed so far; no other weather events have been observed to have changed*. The projections for 2050 and 2100 still show virtually no anticipated increases in severe weather, even though for these columns the IPCC used the exaggerated RCP8.5 scenario (Section 4.2).

### 8.10 Analysis of CONUS data

Extremes in temperature and precipitation are generally events of short duration that often disrupt infrastructure and therefore human health and thriveability. Indeed, the ability of any surface-dwelling species to live productively is somewhat constrained by these near-surface air temperature or precipitation extremes which in essence create the bounding limits for survival. The issue here is whether these extremes, and their attendant potential danger, may be changing in response to increases in infrared-absorbing greenhouse gases (*GHGs*) (e.g., IPCC AR6 Seneviratne et al. 2021).

Unfortunately, the sample of time from which we are able to quantitatively analyze the variations of extreme events is quite brief, around 130 years. This period certainly does not begin to contain all of the extreme events that the climate system, ~~driven by the interaction of two turbulent and chaotic fluids (the atmosphere and ocean),~~ is able to generate. ~~One should appreciate that~~ Over geologic time the climate system has generated an (essentially) infinite variety of patterns and extremes which we humans have never observed, and thus which do not enter our databases from which extreme statistics are determined [see 6.4]. Thus, assuming that a new climate pattern or event in our lifetime is somehow the result of enhanced GHG concentrations requires ~~one to restrict the climate system's wide capabilities in order to conclude~~ the assumption that natural variations are insignificant. This is especially true for precipitation events. With this caveat in mind we will examine the evidence for changes in weather and climate extremes.

#### Extremes in daily temperatures in the Conterminous US (CONUS)

~~Available to us are~~ Daily maximum temperatures in the warm season (TMax, May-Sep) and daily minimum temperatures in the cold season (TMin, Dec-Mar) are available, beginning in Dec 1898 (126 years). The dataset consists of 1,211 CONUS stations designated as United States Historical Climate Network or USHCN stations (Quinlan et al. 1987, Karl et al. 1990). These stations were selected by NOAA as having the fewest problematic issues with gaps, station moves and instrument changes. Where gaps still exist, nearby stations (bias-corrected) were merged so that the median volume of data available for a station is 98%. Although errors certainly reside in the dataset, with over 1,000 stations any underlying signal we discover ~~should~~ can be characterized by relatively high confidence.

#### Daily record extremes in TMax and TMin

Has the occurrence of daily record high or low temperatures changed since Dec 1898? Each warm-season has 153 days (1 May to 30 Sep) and each cold-season has 122 days (1 Dec to 31 Mar, ~~includes 29 Feb~~). For each of these days and each of the stations we calculated the year in which the record highest (lowest) temperature occurred. With 126 years of observations, we would expect, on average, that a station would experience an average each year of 1.21 records for TMax

and 0.96 records for TMin records for TMax (TMin). Figure X indicates the distribution in time of the occurrence of these extreme events.

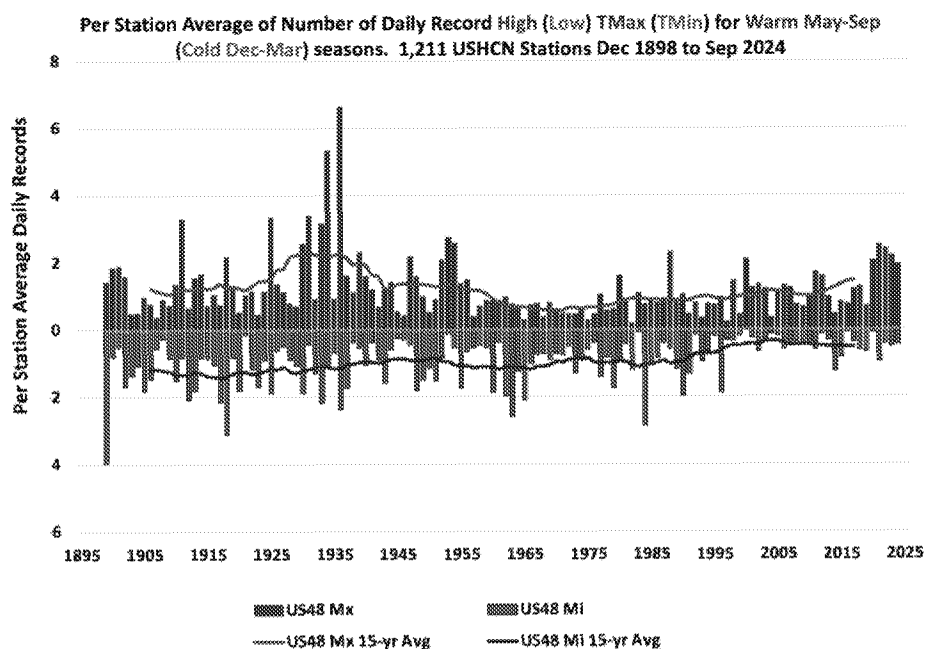


Figure X. Per station average of number of daily record High (red) and Low (blue) for warm and cold seasons in the CONUS. The lines represent 15-year running, centered average. Source: 1,211 USHCN stations supplemented as needed to achieve a minimum of 92% of observations in the 126-year period since Dec 1898.

The results indicate a common feature in many metrics of warm-season extremes in the CONUS - the exceptional heat of the 1920s and especially the 1930s. On the cold side other extreme, the Valentine's Day Arctic outbreak in Feb 1899 stands as the most extensive cold extreme experienced by the CONUS, with 1917 2<sup>nd</sup>. Overall, the number of cold records has declined, especially over the past 25 years.

Heat Threshold



Under the heading of “The Risk of Temperature Extremes is Changing”, the most recent US National Climate Assessment report (NCA5) notes the increase in a threshold metric of number of days at or above 95°F, stating,

*“The western US has been particularly affected by extreme heat since the 1980s ..., experiencing a larger increase in days over 95°F, as would be expected given the greater warming in that region relative to the eastern US.”*

Is the occurrence of 95°F days changing? As a non-parametric statistical variable, a threshold statistic can be misleading. A region with many stations which have near 95°F TMax average temperatures in the summer might see large swings in the metric when only small changes in average temperature occur. Elsewhere with stations that either rarely or virtually always achieve 95°F TMax temperatures, a small change will not impact the results much at all. In the past 126 years, the average CONUS station experienced 129 days per 6-yr period, but the regional values range from 249 in the Pacific Southwest to 9 in the Northeast. Thus, one needs to view such threshold analyses with caution.

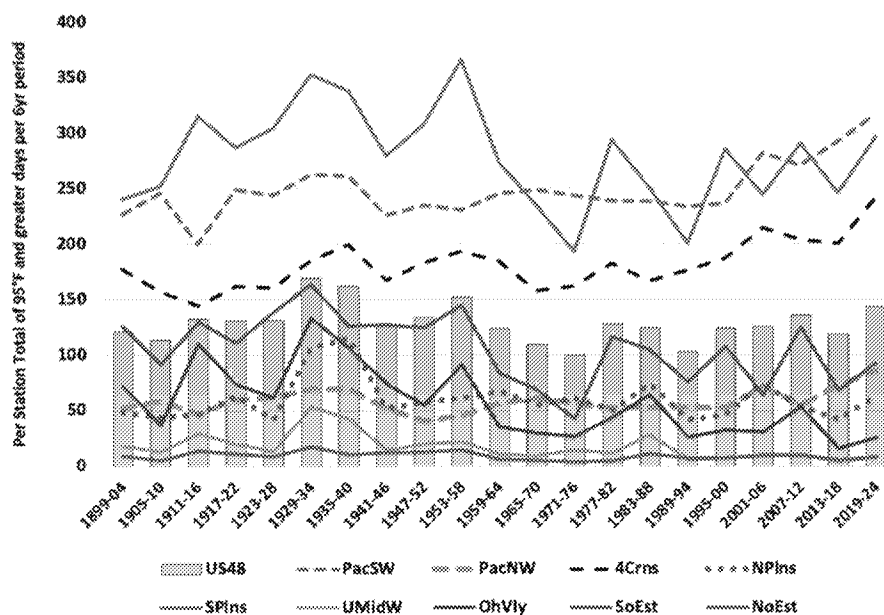


Figure X. Per station average of total number of days > 94°F in 6-yr periods.

In Fig. X we see that only three of the nine regions, all in the West, have experienced upward trends for 95°F or hotter days. The entire CONUS and the other six regions have experienced declines. The Heading “The Risk of Temperature Extremes is Changing” suggests positive trends are now being observed, but that is not evidenced in the combined results of Fig. X. That the “Risk” is changing can thus be applied only to forecasts which is addressed in section XX

### Heatwaves

Of more impact than a single daily record is the phenomena of heatwaves, or consecutive days which exceed an extreme threshold. For this study, the metric will be the number of “Heatwave Days” defined as the sum of all days in May-Sep each year which exceed the 90<sup>th</sup> percentile on consecutive days of at least seven days in length. IS 7 the conventional length? We use 3 days in our weather forecasting

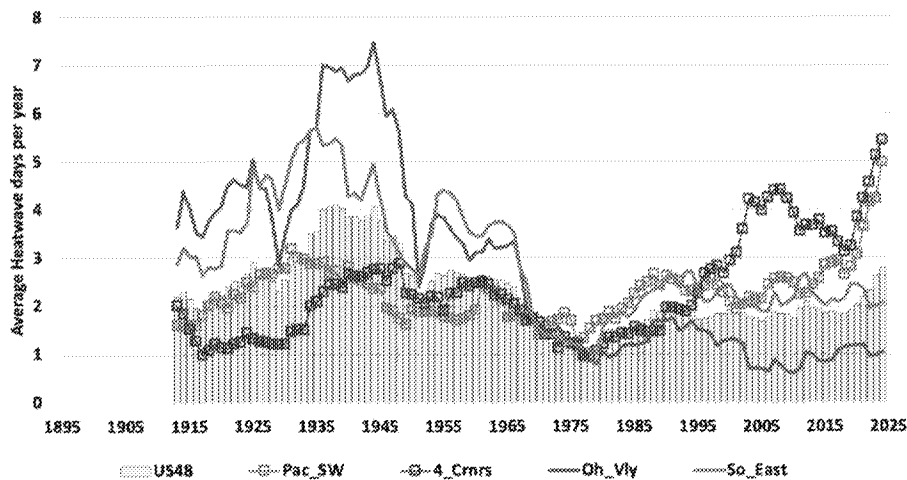


Figure X 15-year trailing average of number of heatwave days per year per station in the CONUS (bars) and four regions: Pac\_SW (orange squares, CA, NV), 4\_Crnrs (red squares, AZ,NM,UT,CO), Oh\_Vly (blue, MO, IL, KY, TN, IN, OH, WV) and So\_East (green, MS, AL, GA, FL, SC, NC, VA).

Figure X indicates again the excessive heat of the first half of the 20<sup>th</sup> century, primarily in the eastern two-thirds of the nation, as seen in the sub-regional values for the Ohio Valley and the Southeast as examples. The West has seen a recent increase of heatwave days and the two sub-regions with the highest number are shown, the Pacific Southwest and the Four-Corners (NCA5). This indicates that the background warm season circulation favored heatwaves in the eastern portions of the country in the first half of the 20<sup>th</sup> century, but in the 21<sup>st</sup> century the patterns have favored heatwaves in the West.

Regarding a different heatwave metric, NCA5 directs readers to the website [ [HYPERLINK "https://www.globalchange.gov/indicators/heat-waves"](https://www.globalchange.gov/indicators/heat-waves) ] (USGCRP 2023) to view the number of urban heatwaves by decade from the 1960s. The figure reveals a monotonic increase in each decade from 2 in the 1960s to 6 by the 2020s. The definition of a heatwave is unusual here - a period of at least 2 consecutive days when the apparent minimum temperature (combination of temperature and humidity) exceeds the 85<sup>th</sup> percentile. More importantly, the dataset is limited to the 50 largest cities in the US.

These results presented in USGCRP (2023) are entirely reasonable, but for reasons unrelated to GHG emissions. Urbanization in these cities is a major factor in the rise of TMin relative to TMax and to TMin at rural stations. Also, the decades of the 1960s and 1970s were the two coldest decades since the 1910's, so the starting date preconditions the time series to show warming. This does not dismiss the real rise in nighttime temperatures in major US cities and the impacts associated with these changes. However, we note for a variety of reasons, that summer TMax (especially in rural areas) serves as better response variable for detecting potential changes in heatwaves influenced by changes in the background climate due, for example, to increasing GHGs - our concern in this document (Christy et al. 2009). For the CONUS as a whole, the evidence in this section suggests GHG emissions have had little-to-no effect on heatwaves in the CONUS.

#### Range of extremes

In the metrics above and other heat indices, a common feature emerges in which the range of CONUS temperature extremes has experienced a decline in the last 126 years.

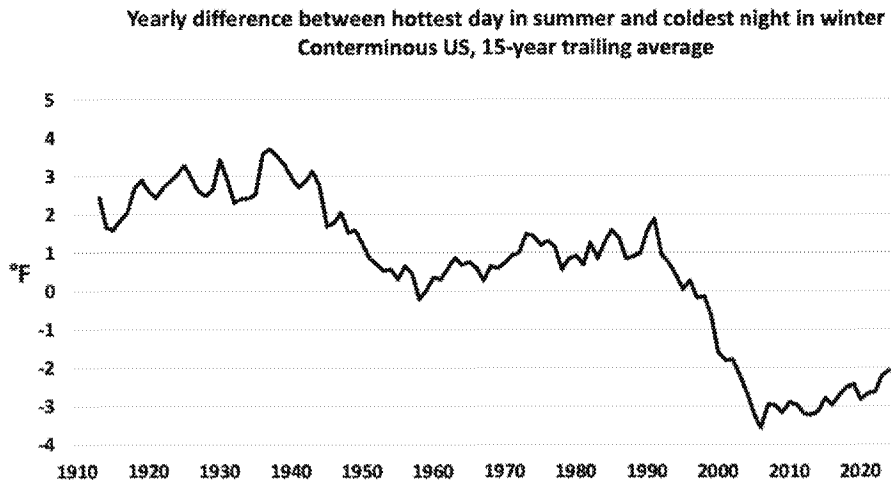


Figure X. 15-year trailing average of the difference each year of each station's hottest warm-season TMax and coldest cold-season TMin relative to the long-term average.

Figure X shows that the average difference for each station between the hottest summer TMax and coldest winter TMin has declined about 5°F in the past 126 years. The decline is due mostly to warming winter TMin, but a decline in the magnitude of summer TMax is also a factor. The rise in TMin has been strongly related to the growing presence of manufactured surfaces around the weather stations over the last 100+ years (Spencer et al. 2025).

The information from these (and other analyses) indicates that any change in daily temperature extremes is difficult to ascribe to enhanced GHG concentrations.

I COVER THIS CASE IN THE ATTRIBUTION CHAPTER, CH 6 I think. I WOULD MOVE SOME OF THIS TO CHAPTER 6 and NOT INCLUDE HERE???

*A Sidebar? – PacNW Heat Wave*

*Under the heading "The Risk of Temperature Extremes is Changing" the NCA5 states: "Several major heatwaves have affected the US since 2018, including a record-shattering event in the Pacific Northwest in 2021."*

*Firstly, the statement that several heatwaves have occurred in the US since 2018 is not evidence in support of the statement that the “Risk” of these events is changing, unless the change NCA5 is suggesting is that we will see fewer heatwave events in the future since there has been an observed decline over the past 126 years (Fig X).*

*Does the June 2021 Heatwave support the claim that the “Risk” is changing? The 2021 event in the Pacific Northwest was indeed significant, being accompanied by temperatures well-above previous “all-time” (i.e., in the last ~125 years) records. Early claims stated the event was decidedly influenced by GHG concentrations and was a sign of things to come (e.g., Philip et al. 2022) though others were more cautious (e.g., Overland 2021, Thompson et al. 2022, White et al. 2023).*

*Mass et al. 2024 performed a detailed analysis of the event and demonstrated that this was truly a “Black Swan”, or an extremely rare event, outside of the range of the small historical sample available to researchers (1895-2021). Their final remark was “Global warming may have made a small contribution, but an extreme heatwave, driven by natural variability, would have occurred in any case.*

*The event’s remarkable nature, magnitude and rarity are indicated by the fact the deep tropospheric temperature anomaly in the Pacific Northwest for the pentad dated 25-29 June 2021 was +11 °C, representing the hottest single summer NH grid point anomaly in the 46-year satellite record which contains over 4 million values. In terms of “all time” record high surface temperatures, over 60% of stations in WA and OR achieved theirs in 2021. However, with the removal of this single event, the time series of “all time” record TMax’s in WA and OR shows a decline since 1911, suggesting there is no pattern of increasing hot extremes. As to model projections of heat waves in the Pacific NW, Mass et al. state, “projected circulation changes associated with global warming show no evidence of amplifying the synoptic features associated with Pacific Northwest heatwaves.” These results suggest the heatwave of 2021 does not readily support evidence of a change in the Risk of extreme temperature events.*

Extremes in daily precipitation.

Due to its stochastic and episodic character, precipitation requires careful statistical treatment to understand variability over long time periods. Of concern in this report is the reasonable assumption that warmer air has a greater capacity to hold moisture and thus if the atmosphere warms (a GHG response), this which could lead to extreme events of greater frequency and/or magnitude. In addition, precipitation processes are more efficient as the environmental air warms, potentially increasing the rain rates as well. NOT NECESSARILY TRUE. COLD RAIN PROCESSES INVOLVING ICE CRYSTALS ARE MORE EFFICIENT; LOWER EFFICIENCY OF COLD RAIN PROCESSES IF TEMP WARMS

The US National Climate Assessments (NCA4, NCA5) have highlighted an increase in the occurrence of the heaviest precipitation events (defined in different ways) primarily in the eastern half of the CONUS, especially the Northeast, when starting in either 1901 or 1958. Interestingly, the regional variations indicate that the largest increases in extreme events are in the Northeast and least in the West, which is counter to the changes in temperature extremes shown above.

McKittrick and Christy 2019 examined long-term and consistent station observations of daily precipitation to test some of these NCA claims for the Southeast and West Coast. In neither case when the time series were extended back in time (as far as 1872 in some cases) or when starting later (1978) were the trends significant. We update these findings with similarly constructed observations from 29 stations on the Pacific Coast (1893ff from San Diego CA to Blaine WA), 24 stations in the humid Southeast (1872ff from Austin TX to Washington DC), and 21 stations in the Northeast (1888ff from Buffalo NY to Portland ME – the region where trends are greatest).

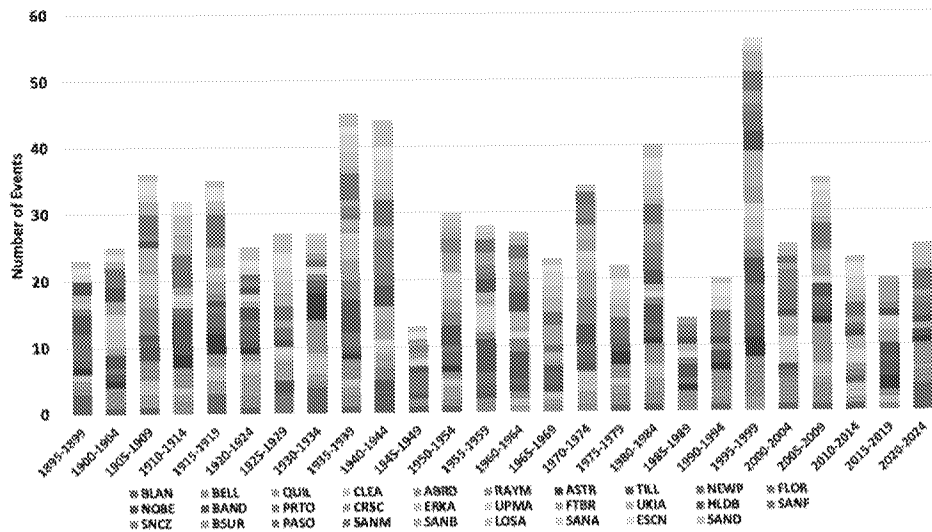


Figure X. The time distribution by 5-year periods of the 26 heaviest occurrences for each station (i.e., nominal 1-in-5 year event). I FIND THIS DIAGRAM VERY DIFFIULT TO INTERPRET, EVEN THE STATION NAMES

The Pacific Coast receives considerable amounts of precipitation from Atmospheric River (AR) events which often last more than a day or two. In Fig. X we show the distribution in time of the 26 heaviest 5-dy precipitation totals (nominal 1-in-5yr occurrence). The deluges associated with the massive 1997-98 El Niño event are readily apparent. While erratic, as is typical of these types of precipitation metrics, there is no indication of a tendency to change over time.

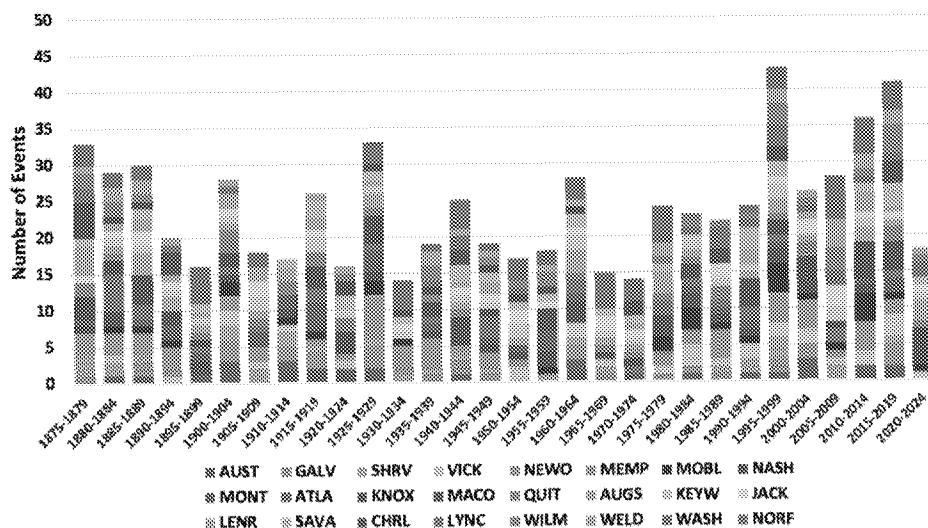


Figure X. As above but for the 30 heaviest 1-in-5yr events for 24 stations in the humid Southeast from Austin TX to Washington DC in 5-year bins for 1875-2025.

INCLUDE THE HUGE AR from 1861/1862 I THINK THIS IS WORTH A MENTION

The event is similar to the exceptionally intense California storms that occurred between December 1861 and January 1862, which dumped nearly 10 feet of rain in parts of California

and submerged the entire Central Valley under as much as 15 feet of water.<sup>67,68</sup> Six megastorms more severe than 1861–1862 have occurred in California during the last 1800 years, occurring at intervals of 200 years or so.<sup>69</sup>

1 William Brewer, *Up and Down California in 1860–1864 The Journal of William H. Brewer* (Berkeley, CA: University of California Press, 1930).

2 Keith Porter et al., *Overview of the Arkstorm Scenario* (Reston, VA: Dept. of the Interior, U.S. Geological Survey, 2011).

3 Jan Null and Joelle Halbert, "California Washed Away: The Great Flood of 1862," *Weatherwise* 60, no. 1 (2007): 26–30, <https://doi.org/10.3200/wewl60.1.26-30>.

The temporal pattern of 5-day totals of the 1-in-5yr heavy events in the humid Southeast is generally unremarkable, though a cluster of higher values appears in 1995 to 2019. The increase in those years is due largely to the 4 northeastern-most stations of Wilmington NC, Weldon NC, Washington DC, and Norfolk VA. This confirms the pattern indicated in NCA4 and NCA5 of a tendency for an increasing frequency of heavy events, due to a temporal clustering of tropical



storms, from eastern NC to Maine discussed below. Otherwise, the remaining 20 stations show an unremarkable temporal distribution of heavy events.

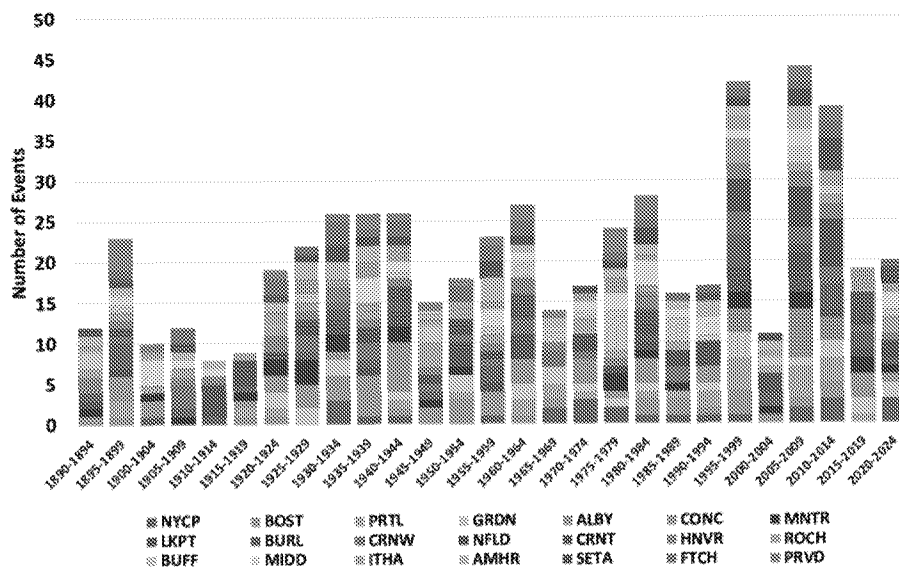


Figure X. Time distribution of the heaviest 27 (1-in-5yr) heaviest 3-day precipitation events for 21 stations from NY to ME, including Montreal. AGAIN I FIND INTERPRETING THIS FIGURE VERY DIFFICULT

In Fig. X is displayed the 27 (1-in-5yr) heaviest 3-day events for the last 135 years in 21 stations in the Northeast (including Montreal Canada). We use 3-day totals here as this produced the largest variations in time. In this region, 72% of the events occur during June to October and are dominated by tropical incursions of hurricanes, tropical storms or tropical storms that transition to extratropical systems.

Howarth et al. 2019 report differences in the Northeast between two 18-year periods: 1979-96 and 1997-2014 (a similar region as in Fig. XX that includes PA and NJ) of various precipitation extremes, one of which indicated a dramatic increase (317%) in the 24-hr events > 6 inches. This high increase is due to the very small numbers of such events of which there were only 6 in the first

period and 25 in the second. Most of the stations did not record such an event suggesting these erratic, episodic events over brief, 18-yr periods, need scrutiny by additional statistical methods.

Using the information in Fig. X over the same years as Howarth et al. we find an increase of the frequency of heavy events between the two periods of 51%. One can see in Fig. X that it was unfortunate that Howarth et al. ended in 2014 prior to a return to the long-term average of such events.

A feature of Howarth et al. is the use of single day totals which is questionable because extreme events are often spread across the observation time boundary, so that stations measuring at 0700 LT versus those at Midnight will have differing results and which would then have major impacts on counting rare events. We use the 3-day totals in Fig. X to be sure to capture the extent of these short events. In any case, we can confirm that the period 1997 to 2014 provided a cluster of heavier events as Howarth et al. have documented.

Howarth's most remarkable claim (317% increase in 6" days) is potentially misleading because it is a threshold statistic (see above under Heat Threshold) and a ratio of small numbers over a short period. The result is not representative of *relative* extreme events for the whole region since the majority of stations never experienced a 6" total. Fig. X above determines the same number of events for each station (27 heaviest events) whose heaviest events ranged from 4.4" to 12.5" and 27<sup>th</sup> heaviest event ranged from 3.3" to 5.0". This analysis thus normalizes the extremes so each station is equally represented. Note too that the period of record here is 135 years vs. 36 years of Howarth et al. Except for three 5-year periods between 1995 and 2014 there is nothing statistically remarkable about the results.